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Second Series *December, 1920* *Vol. XVI., No. 6*

THE

PHYSICAL REVIEW.

ON K. S. MAGNET STEEL.

By Kôtarô Honda and Shôzô Saitô.

Synopsis.

K. S. Magnet Steel.—The composition of this steel is given as C 0.4–0.8 per cent.; Co 30–40 per cent.; W 5–9 per cent.; Cr 1.5–3 per cent. *Tempering* is best effected by heating to 950° C. and quenching in heavy oil. Measurements of the *residual magnetism* for specimens of different composition gave values from 920 to 620 C.G.S. units; the *coercive force* for the same specimens ranged from 226 to 257 gauss. *Artificial aging* by heating in boiling water and by repeated mechanical shock reduced the residual magnetism by only 6 per cent. The *hysteresis curves* for a magnetizing force of ± 1,300 gauss were taken for annealed and tempered specimens; for the annealed specimen the coercive force was 30 gauss and for the hardened steel the coercive force 238 gauss and the energy loss per cycle 909,000 ergs. The *hardness* of annealed and tempered specimens was found to be 444 and 652 respectively on the Brinnell scale and 38 and 55 on the Shore scale. The *microstructure* of the hardened steel showed a finer grain than for the annealed.

ON June, 1917, a new remarkable alloy steel possessing an extremely high coercive force and a strong residual magnetism was discovered by Mr. H. Takagi and one of the present writers (K. Honda). This steel is prominent as a magnet steel among those hitherto known, *i.e.*, tungsten magnet steel, and is named the "K. S. Magnet Steel," after Baron K. Sumitomo, who offered a sum of 21,000 yen to our university for the investigation of alloy steels. During the last two years, several important improvements have been made in the steel, and also numerous measurements of its characteristic constants made; but for reasons connected with the patent, the publication of these data has been suspended up to the present. In the following pages, a short account of the result of our investigation is given.

The alloy is a speical steel containing cobalt tungsten and chromium. A favorable range of the percentages of these metals is given below:

C	Co	W	Cr
0.4–0.8%	30–40%	5–9%	1.5–3%

The alloy being somewhat brittle, great care is required in forging the ingot; but with a good deal of practice, one can forge it into any desired shape. For K. S. magnet steel, the best quenching temperature is 950° C., and the best quenching bath a heavy oil. As shown below, K. S. magnet steel requires almost no heat treatment in order to be used as a permanent magnet in electrical instruments.

The following sets of measurements for K. S. magnet steel are described below:

(*a*) Values of residual magnetism and coercive force.
(*b*) Hardness and microstructure.
(*c*) Hysteresis curves for annealed and quenched steels.
(*d*) Effect of artificial aging,
  (i) Heating in boiling water,
  (ii) Mechanical shock.
(*e*) Effect of the dimension of the specimen on residual magnetism.

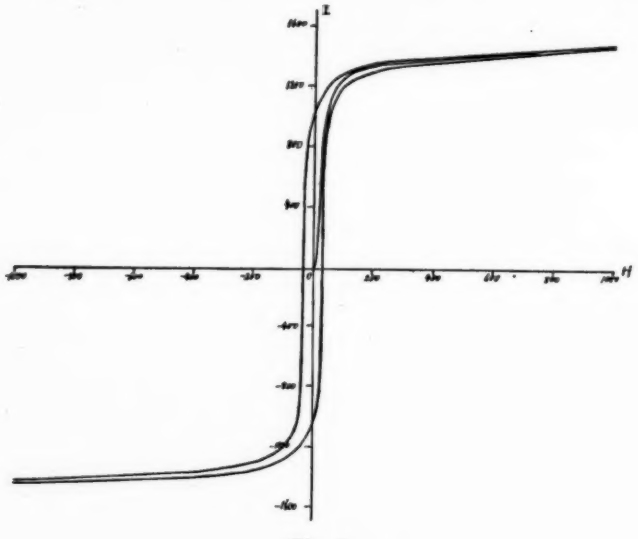

Fig. 3.
Annealed specimen.

The specimens were tested in the form of a cylindrical rod, 20 cm. long and 5 mm. thick. The intensity of magnetization was measured by the ballistic method in the usual way. The magnetizing coil was 40 cm. long and wound in thirteen layers with an insulated copper wire about 1.5 mm. thick, the coil constant being $4\pi n = 483.4$, where n is a number of turns in unit length of the coil. The effective field H was calculated by the well-known relation

$$H = H' - IN,$$

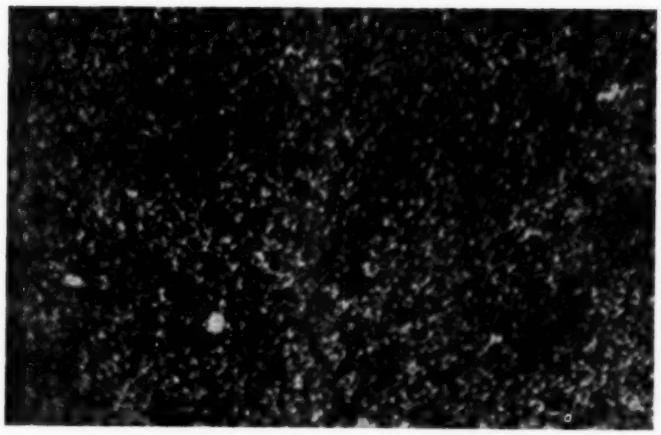

Fig. 1.

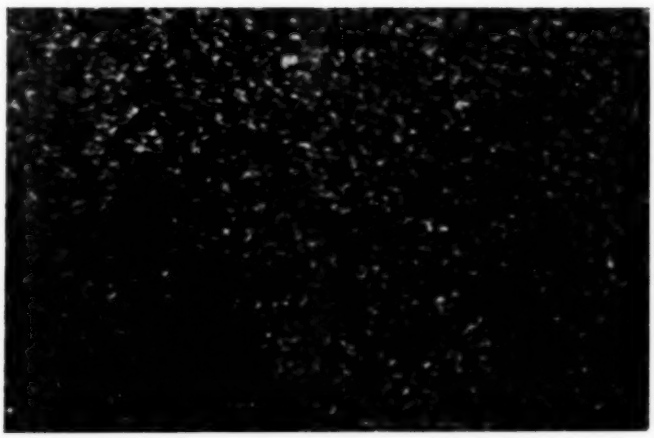

Fig. 2.

K. HONDA AND S. SAITO.

where H' is the applied field, I the intensity of magnetization and N the demagnetizing factor.

Residual Magnetism and Coercive Force.—Two important quantities for a permanent magnet are the intensity of residual magnetism I_r and coercive force H_c, of which the latter is more important than the former. Since these quantities increase with the magnetizing field, a strong field of about 1,500 gausses was applied in our experiment. By varying the percentages of carbon, tungsten, cobalt and chromium within certain limits, alloys having different values of I_r and H_c can be obtained. The following table contains some of the values hitherto obtained:

Specimen.	I_r (C.G.S.).	H_c (ganss).
No. 1	920	226
2	841	221
3	828	245
4	620	257

Thus the coercive force is about three times greater than that of the best tungsten steel hitherto known. The residual magnetism is also greater than that of the tungsten steel.

Hardness and Microstructure.—The hardness of a steel is closely related to its microstructure. Generally speaking, the harder the steel, the finer the structure. The Brinell and the Shore hardness of an annealed and quenched K. S. steel are given in the table below:

	Brinell.	Shore.
Hardness (annealed)	444	38
" (quenched)	652	55

In Figs. 1 and 2, the microphotography of annealed and quenched K. S. steel is given; the microstructure of these specimens consists of an aggregate of very fine grains.

The hardness is also intimately related to magnetism; *i.e.*, mechanically hard steel is also magnetically hard. Thus, since K. S. steel is mechanically very hard and has a very fine structure, it cannot be easily magnetized; but when it is once strongly magnetized, its residual magnetism is very large, and cannot easily be lessened.

Hysteresis Curves.—The following table contains the results of observation for the intensity of magnetization in different fields, both of the annealed and quenched states of the same specimen.

These numbers are also plotted in Figs. 3 and 4, together with the hysteresis loops for the cyclic change of magnetizing field between

Annealed.		Quenched.	
H (Gauss).	*I* (C.G.S.).	*H* (Gauss).	*I* (C.G.S.).
19	281	53	54
30	805	91	107
78	1,227	200	365
247	1,372	295	909
377	1,410	344	998
675	1,450	581	1,171
776	1,465	870	1,266
960	1,479	982	1,293
1,322	1,499	1,281	1,346

+ 1300 and − 1300. In the annealed state, the coercive force is only 30 gausses; but in the quenched state, it amounts to 238 gausses and the area of the loop is enormously large, the loss being about 909,000 ergs. In the best tungsten steel, the same quantity is found to be 290,000 ergs.

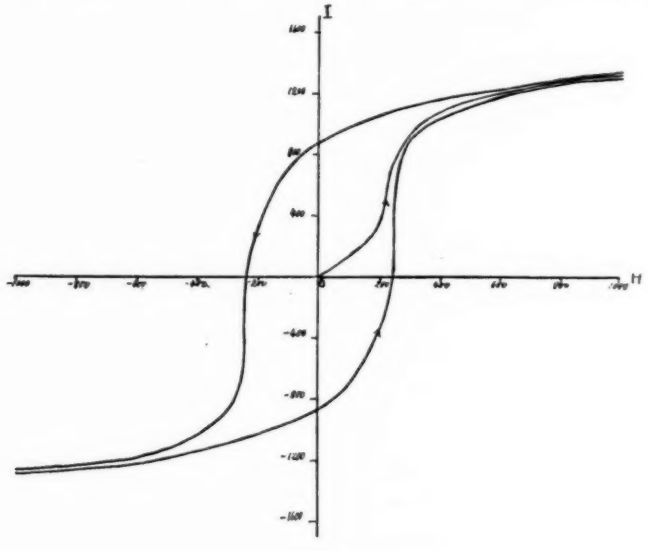

Fig. 4.

Quenched specimen.

Effect of Artificial Aging.—A permanent magnet is always acted on by a demagnetizing force due to the end distribution of magnetism; this force rapidly increases, as the dimension ratio of the specimen decreases. The heating process of the specimen is to expose it to molecular vibrations under the action of the demagnetizing force, and hence residual magnetism is usually reduced by a considerable amount during a prolonged heating, especially in a short specimen, for which the demagnetizing force is large. Since K. S. steel has a large coercive

force, it may be expected strongly to resist the weakening effect of prolonged heating.

The effect of heating the specimen in boiling water is graphically given in Fig. 5, *a*. A rod of K. S. steel having the same dimensions as before was quenched, and strongly magnetized in a coil. The specimen was afterward constantly heated in boiling water, and its residual magnetism measured from time to time for 40 hours. From the curve, we notice that during the first heating for three hours, the residual magnetism slightly increases and afterwards remains perfectly constant. In other K. S. magnet steels, it is usual to observe a slight decrease of magnetization for the first one or two hours of heating, and then an increase to its former value at about three hours, the magnetization afterwards remain-

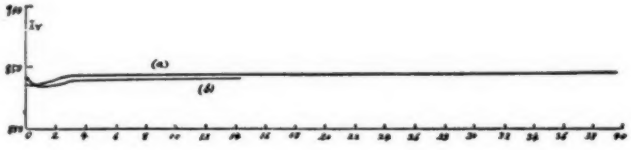

Fig. 5.
Decay curve in boiling water.

ing constant (curve *b*). This decrease and increase of magnetization are due to the simultaneous action of two opposite causes. The first decreasing cause is the molecular vibration due to heating, and the second increasing cause the tempering; that is, during heating, a small fraction of carbides, which are present as a solid solution, is set free, and hence the magnetism increases. The effects of these two causes soon reach their asymptotic values as the heating continues. Hence the superposition of these two effects results in the decay curve (*b*), as actually observed. When the first effect is very small, the curve takes the form as shown in curve (*a*).

The effect of a repeated shock was also observed; a specimen of the same dimensions as before was quenched and magnetized by a strong field; it had initially a residual magnetism of 854 C.G.S. units. Two series of experiments were made; in one, the specimen was repeatedly allowed to fall on a wooden floor from a height of one meter, and in the other, on a concrete floor from the same height. The result of experiments is graphically given in two curves in Fig. 6. The ordinate is the residual magnetism and the abscissa the number of falls. The first diminution of magnetization is comparatively rapid up to 20 falls, and afterwards very slow. The fall on the concrete floor has a greater demagnetizing effect by about 6 C.G.S. units than the fall on the wooden floor. After 850 repeated falls on the concrete floor, the intensity of residual magnetism diminished from 854 to 800 C.G.S. units.

Effect of Dimensions on Residual Magnetism.—As the dimension ratio of a permanent magnet decreases, the demagnetizing force acting in the

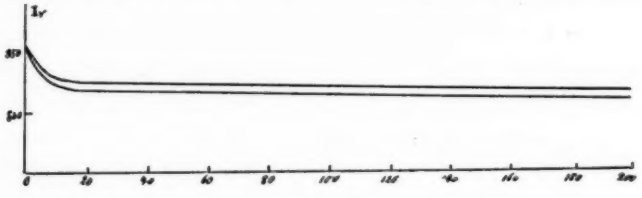

Fig. 6.

I_r—fall number curve.

interior of the magnet becomes greater, and hence the residual magnetism rapidly decreases with the dimension ratio. The resistance to this demagnetizing action is measured by the coercive force. Suppose the length of a bar magnet be gradually diminished, then the material having a smaller coercive force undergoes a greater diminution of magnetism than one having a greater coercive force. Hence, for a bar magnet, K. S. magnet steel has a very great advantage over the ordinary tungsten steels. For a dimension ratio of 15, the permanent magnetism of K. S. magnet steel is about 1.8 times stronger than that of the tungsten steel.

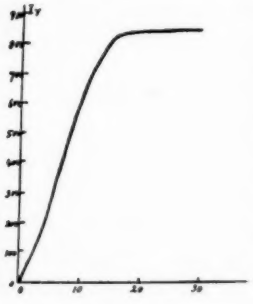

Fig. 7.

I_r—dimension ratio curve.

In Fig. 7, the I_r-dimension ratio curve for K. S. magnet steel is given. It shows how rapidly the residual magnetism increases with the increasing ratio of the dimensions, and that above the ratio of 20, the residual magnetism is not affected by the ratio.

SUMMARY.

1. K. S. magnet steel has an extremely large coercive force; its intensity of residual magnetism is also considerably larger than that of ordinary tungsten steels.

2. The area of the hysteresis loop of K. S. magnet steel is very large.

3. K. S. magnet steel, when quenched, is mechanically very hard, and has a very fine microstructure.

4. The residual magnetism of K. S. magnet steel does not appreciably diminish by a prolonged heating at 100° C. over many hours.

5. 850 repeated falls of the steel bar from a height of one meter on a concrete floor causes only a diminution of magnetization by 6 per cent. of its initial value.

6. K. S. magnet steel is specially suited for short bar magnets.

THE EFFECT OF FLUORESCENCE AND DISSOCIATION ON THE IONIZING POTENTIAL OF IODINE VAPOR.

BY H. D. SMYTH AND K. T. COMPTON.

SYNOPSIS.

Fluorescence and ionization.—When fluorescing under the influence of the mercury green line, *iodine vapor* shows weak ionization at a potential about 2.6 volts less than the normal ionizing potential. This is attributed to ionization by impact against molecules whose electrons have been displaced by absorption of the exciting radiant energy.

Dissociation and ionization.—Another weak ionization always observed at about 1.5 volts less than the normal ionizing potential was attributed to ionization of atomic iodine, present as result of the dissociating action of the hot filament. This was verified by experiments in a pyrex glass apparatus at such high temperatures as to cause a high percentage of dissociation, when it was found that this new type of ionization was very intense.

The observed ionizing potentials were: 6.8 volts, due to fluorescing molecules; 8 volts, due to iodine atoms; 9.4 volts due to iodine molecules. The difference between the first and last values corresponds roughly to the *quantum* of absorbed radiant energy, while the difference between the two latter values agrees accurately with the *heat of dissociation* of iodine molecules.

PART I. FLUORESCENCE.

Introduction.

ACCORDING to present theories of atomic structure an electron in an atom is in stable equilibrium only in certain definite positions or orbits and the transfer of an electron from one position to another is accompanied by the absorption or emission of energy. In an atom of gas in the normal state the electrons are grouped as closely as possible about the center leaving the outer, less stable, orbits unoccupied. On the other hand, during the emission of light, as has been very clearly set forth in a recent paper by Drs. Foote and Mohler,[1] an electron is supposed to be falling back toward the normal oribit after having been knocked wholly (ionization) or partly out of the atom. Careful researches by Whiddington[2] and by Henry[3] have failed to detect any ionization in fluorescing iodine vapor. Apparently, therefore, since fluorescence is not accompanied by ionization, it must result from the temporary dis-

[1] Phil. Mag., 40, p. 80, 1920.

[2] Whiddington, Proc. Camb. Phil. Soc., 15, p. 189, 1909.

[3] Henry, Proc. Camb. Phil. Soc., 9, p. 319, 1898.

placement of an electron to one of the outer orbits. On this hypothesis it is obvious that the work required to ionize a fluorescing atom or molecule should be less than that necessary to ionize an atom or molecule in the normal state. As suggested by Hughes,[1] this is probably the explanation of the results of Franck and Westphal,[2] who found the current in a glow discharge through iodine increased by fluorescence. The present research was undertaken in the hope of observing this predicted reduction in the ionizing potential of iodine vapor, the fluorescence of which has been so thoroughly investigated by Wood.

Apparatus and Procedure.

The ionization tube used was of the ordinary three-electrode type with plate, *P*, gauze, *G*, and filament, *F*, of platinum and a ground-glass joint to allow replacement of the filament. As will be seen from the diagram in Fig. 1, its only unusual features are its dimensions. The

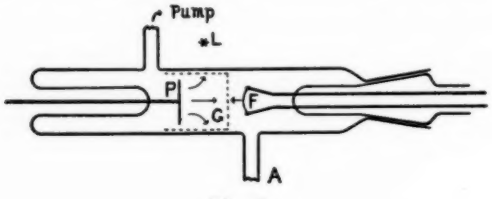

Fig. 1.

diameter of the tube was made small, about 1.5 cm., in order that the exciting light might not be too greatly cut down by the absorption of the vapor before getting into the region where impacting electrons were most numerous. The direction of the retarding field resulting from the shape of the gauze tended to spread the electrons toward the walls of the tube and was thus a second factor favoring impact of electrons with fluorescing molecules. An accelerating field was applied between *F* and *G* and a retarding field larger by a constant amount, between *P* and *G*. The gauze *G* was connected to a Leeds & Northrup high sensitivity galvanometer which measured the electronic current between *F* and *G*. The disc *P* was connected to Dolazelek electrometer of sensitivity about 3,000 millimeters per volt, making the capacity of the electrometer system of the order of magnitude of 50 cm. The potentials were read on a Robt. W. Paul voltmeter.

In order to get increased emission the filament was coated with barium oxide. It was found, however, that a very large emission in vacuum was tremendously reduced by the presence of iodine and after a few hours use became so small as to make the detection of minor effects difficult.

[1] A. L. Hughes, Photo-Electricity, p. 21, 1914.

[2] Franck & Westphal, Verh. d. D. Phys. Ges., 14, p. 159, 1912.

To introduce the iodine, the distillation apparatus shown in Fig. 2 was sealed on to the side tube, A, of the ionization tube. The whole system was first heated and pumped out with a Gaede mercury pump for several hours, and a liquid air trap between the pump and the apparatus was given time to take out all mercury vapor. Then the distillation tube at C was opened, Kahlbaum resublimed iodine introduced into M, and the glass again sealed off. Keeping liquid air on M, the pump was started again and after further heating of N and evacuation the iodine was sublimed over into N. Now, by raising N above liquid-air temperature iodine vapor was made to flow through the apparatus to the trap on the other side, thus giving a pressure in the apparatus somewhere between the vapor pressures at the temperature of N and at the temperature of liquid air. By the above procedure and by keeping the pump running continuously, disturbances due to gases evolved by the glass or by the filament were reduced to a minimum.

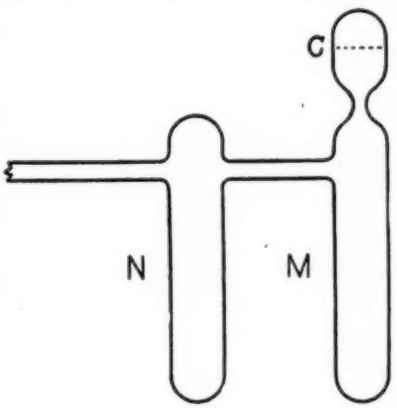

Fig. 2.

To excite fluorescence, a Cooper Hewitt quartz mercury arc was used. It was mounted about 2 in. above the ionization chamber and across it, so that the maximum amount of light fell on the part of the tube between P and G. A sheet copper shutter was arranged so as to completely cut off the light, making possible alternate readings with and without fluorescence.

Since the electrometer system had a considerable zero leak, readings were started with the accelerating field V_A sufficiently low to establish a good zero line. Then V_A was increased in small steps and two readings taken at each value, one with the shutter open and one with it closed. In several runs this was further checked by reading with the shutter closed, then open, then closed again at each voltage. Ionization was, as usual, detected by a sharp change in the rate of deflection of the electrometer. Velocity distribution measurements were made frequently though, as will appear later, no great importance was attached to them.

Experimental Results.

The results of two typical runs are plotted in Figs. 3 and 4 below. In each case there are two curves for each run, one drawn through points

taken with the shutter open (circles) and one through the points with the shutter closed (dots).

On the first of these runs, No. 4, Fig. 3, in the fluorescence curve there are three distinct break points at about 5.5, 6.6 and 8.4 volts respectively,

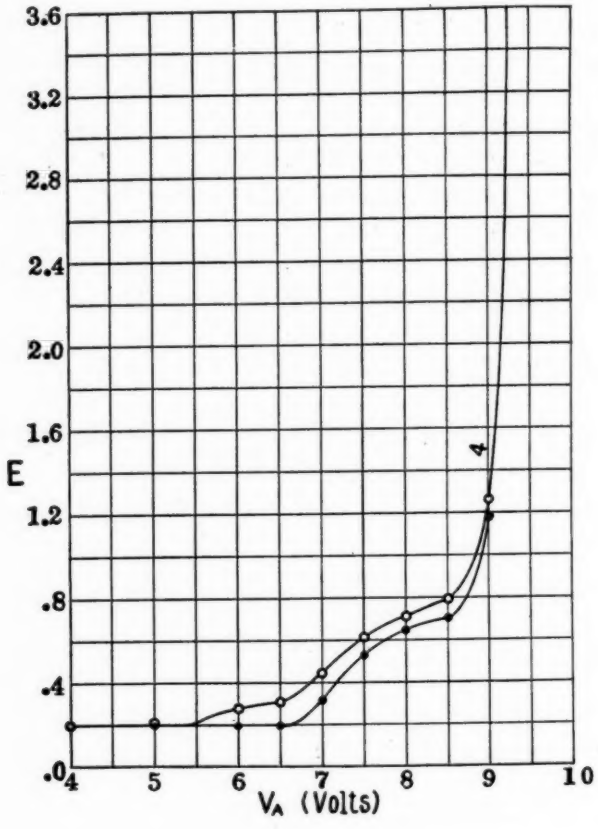

Fig. 3.

but only the two higher of these appear on the normal curve. Run No. 5, Fig. 4, shows exactly the same effects coming at 6, 7.3, 8.5 and 7.4 and 8.5 volts, but the curves rise much less steeply, as would be expected from the fact of smaller emission. Apparently the two lower breaks are due to very improbable types of impact since they both seem to approach saturation rapidly as the voltage is raised. The lowest break appearing only on the fluorescence curves, is naturally attributed to ionization of fluorescing molecules. To explain the middle break which was totally unexpected, the authors were forced to the conclusion that it is due to the ionization of atomic iodine produced by the dissociation of molecules by the hot filament. The correctness of this view was

demonstrated by further experiments which are described in the second part of the present paper. Since atomic iodine has no absorption bands in the visible spectrum[1] it would not be affected by the presence of the mercury arc. All discussion of this second effect will therefore be post-

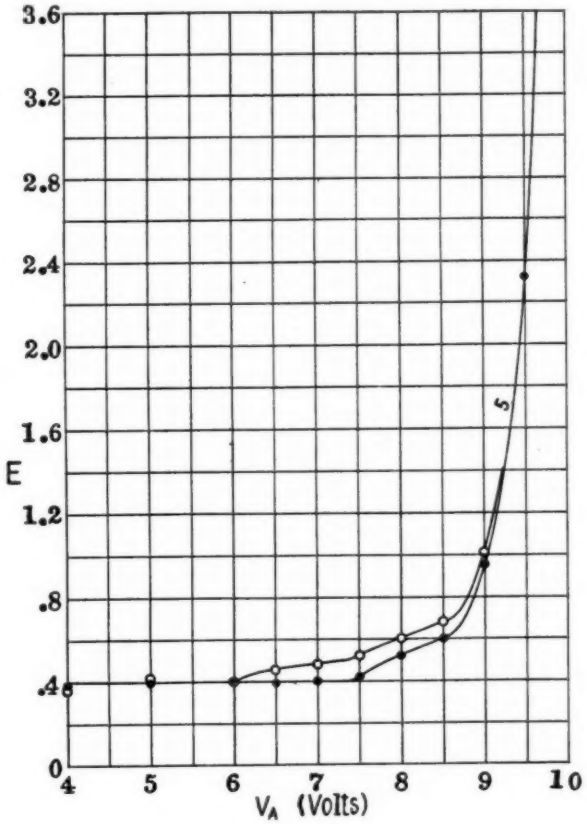

Fig. 4.

poned to the second part of the paper. The third break point which appeared very strongly even with very small emission is presumably due to ionization of normal, unexcited, diatomic iodine vapor.[2] Before further discussion it will be well to present a complete summary of our experimental results.

where

p = pressure in mm. Hg. (approximate),

G = current to gauze in amperes $\times 10^{-9}$.

[1] E. J. Evans, Astro. Phys. J., 32, p. 1, 1910.

[2] F. L. Mohler & P. D. Foote, PHYS. REV., 15, p. 321, 1920.

Discussion of Results.

The values given in this table have been corrected for velocity distribution as nearly as possible according to the formula derived in a previous paper[1] but on account of the shape of the gauze used and the difficulty of estimating the probability of ionization by a collision in iodine, no great degree of accuracy can be claimed, probably considerably less than indicated by the calculated probable error.

However, it is not so much the absolute values of the points a and c which concern us here as it is the difference between them, as given by the last column of Table I., and this is independent of the velocity

TABLE I.

Run.	p.	G.	Corrected Breaks.					
			Fluorescence.			Normal.		$c-a$.
			a.	b.	c.	b'.	c'.	Volts.
1	.005	2.6	6.4		9.		9	2.6
2	.15	14.2	6.9	8.2?	9.5	8.2	9.7	2.6
3	.15	4.9	6.7	8.2	9.7	8.2	9.7	3.
4	1.	155.	6.2	7.3	9.0	7.3	9.2	2.8
5	.25	9.5	6.	7.3	8.5	7.4	8.5	2.5
6	.15	2.5	5.5?	6.7?	8.5		8.5	3. ?
7	1.	700.		8.7?	10.2?	8.7	10.2	
8	1.	150.	6.9	7.8	9.7	7.8	9.7	2.8
9	.13	11.4	7.	8.6	9.5	7.7	9. ?	2.5
10	.13	21.	6.	7.7	9.5?	7.2	9.5?	3.5?
11	1.	11.5	5.7	6.8	8.2	6.8	8.4	2.5
Average omitting doubtful (?) values			6.42 ±0.11	7.67	9.07 ±.42	7.7	9.21	2.66 ±.04

distribution corrections. The mean value of $c - a$, $2.66 \pm .04$ volts, should be the difference in the work necessary to remove an electron from a fluorescent molecule and from a normal molecule. Now the shortest lines observed by Wood[2] in the fluorescent spectrum of iodine excited by a quartz mercury arc are of the group of -1 order having a wave-length about 5370 Å.U. while the wave-length of the exciting light is 5460.7. If we apply the quantum relation to these wave-lengths we get 2.3 volts and 2.26 volts respectively. We would expect, then, 2.3 volts to be the maximum gain in potential energy of a molecule due to fluorescence and the greatest possible shift in its ionizing potential. The value of the resonance potential for iodine found by Mohler and Foote[3] is $2.34 \pm .2$ volts

[1] Smyth, PHYS. REV., 14, p. 409, 1919.

[2] R. W. Wood, Researches in Physical Optics, Part II., p. 29.

[3] Loc. cit.

which would indicate that this is a natural quantum for an iodine molecule to absorb and thus agrees approximately with our last statement.

The discrepancy between this theoretical value of about 2.3 volts and the observed values of $2.66 \pm .04$ may very likely be due to some constant experimental error but this seems sufficiently improbable to make a brief consideration of other more deep-seated possibilities worth while. The first of these is the fact that there is a strong absorption band[1] for iodine in the blue green region corresponding to 2.66 volts and there are lines in the mercury arc at $\lambda = 4358$ and 4916.4 corresponding to 2.83 and 2.51 volts. The iodine molecule might absorb energy in this region but radiate it in two or more steps so that it would not give lines of such short wave-length in the fluorescent spectrum. In this case, however, we would still expect a stronger effect from the much more intense green line.

A second possibility is that, due to the increased radius and instability of a fluorescent molecule, the probability both of collision and of ionization at collision is greatly increased. This ionization effect is therefore much more probable per molecule than an ordinary ionization and therefore tends to be detected at a relatively earlier point on the curve. The much greater number of the normal molecules would counteract this tendency to a greater or less degree.

A third possible contributing factor is the absorption of heat waves from the filament after the molecule has already absorbed the quantum corresponding to 2.26 from the mercury arc. The difference between 2.26 and 2.66, or 0.4 volt, gives a wave-length of 2.09 $\mu\mu$ which would certainly be present in the radiation from the filament.

Finally, the discrepancy between the observed and expected values may be due to the effect of a negative surface layer on the platinum gauze G, tending to repel electrons and consequently tending to make the observed values of V_A greater than the actual values. Such layers are known to occur in the electronegative gases. If present, such a layer would reduce the effective accelerating field to the greatest extent where the electron current is most intense, *i.e.*, near the center of the gauze. The electrons whose impacts contribute most to the ionizaton of fluorescent molecules pass through the gauze near the outside of the tube, while the intensity of the ordinary ionization is due principally to electrons which pass near the center of the gauze. Consequently the observed value of the normal ionizing potential would be shifted more than the fluorescent ionizing potential, and in a direction to account for the discrepancy.

[1] Wood, op. cit., p. 23.

In view of these considerations, the agreement of observed and expected values is probably as good as could be expected. In any case, it is important to have definitely established the effect of fluorescence in decreasing the ionizing potential.

PART II. DISSOCIATION.

Introduction.

According to the results of Starck and Bodenstein,[1] iodine vapor at a pressure of .01 mm. and temperature of 450° C. would be nearly 50 per cent. dissociated or at a pressure of .05 mm. it would be 25 per cent. dissociated. At 500° C. and .03 mm. the degree of dissociation would be about 40 per cent. From this it is evident that any effect due to atomic iodine should be greatly accentuated by running at a temperature between 450° C. and 500° C. if the pressure is kept low. This suggested the following method for investigating the ionization of atomic as distinguished from molecular iodine.

Apparatus and Procedure.

As has already been stated the effect *b* in the experiments on fluorescence was attributed to the ionization of atomic iodine. In order to test this theory a new apparatus, made of pyrex glass, was mounted in an electric heater so that its temperature could be raised to more than 500° C. The electrodes were the same as before but the tube was about twice as long so that each end projected outside the heater. This made it possible to keep the ends of the tube cool and so helped to prevent electrical leaks. Platinum guard rings wrapped around the outside of the tube served the same purpose. The temperature was measured by a platinum resistance thermometer.

The iodine distilling apparatus in this case was connected with a T-joint between the ionization tube and the pump. As before, mercury vapor was kept out by a liquid air trap but now the pressure was regulated by the temperature of a U-tube between the T-joint and the main apparatus, a large amount of iodine being first condensed in it by using liquid air. In this way, using the equation given by Baxter and Grose[2] for the vapor pressure of iodine, and knowing the exact temperature of the U-tube a much more accurate value for the pressure could be obtained than in the previous case, where there was a flow through the tube.

In spite of all precautions the electrical leak at high temperature was serious. It was found, however, that it increased uniformly with voltage

[1] G. Starck & M. Bodenstein, Zs. Elch., 16, p. 966, 1910.

[2] G. P. Baxter and M. R. Grose, J. Am. Ch. S., 37, p. 1061, 1915.

so that a good zero line could be determined for each run by a series of measurements with the filament turned off. Otherwise the procedure was similar to that of the previous experiment.

Experimental Results.

In Figs. 5 and 6 below are given the graphs of three runs which illustrate the confirmation of our theory by this high temperature apparatus. Thus, in run 15, Fig. 5, taken at 515° C., we have both break points appearing at 8.3 and 9.7 volts, respectively, but by comparing with Figs. 3 and 4 we see that the first effect is very much greater than in any

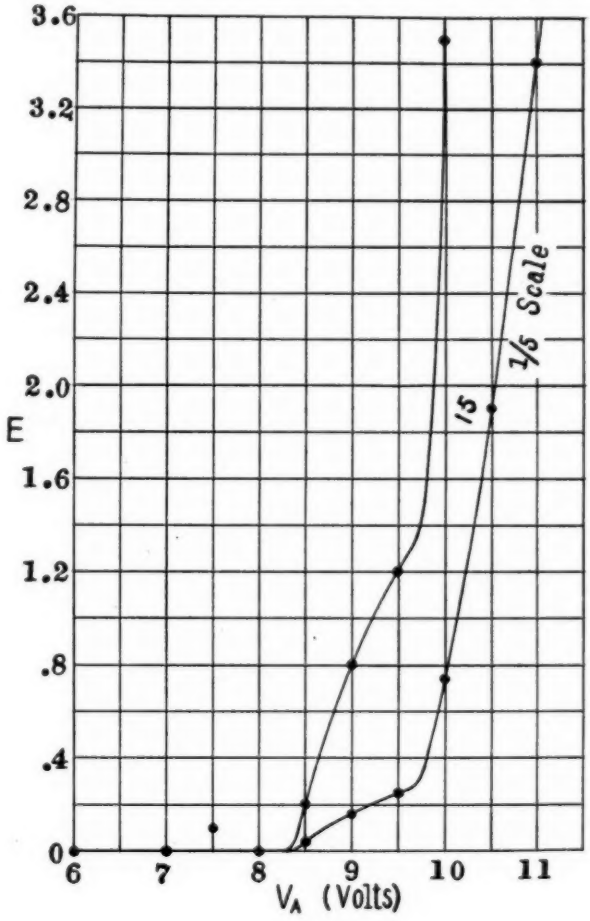

Fig. 5.

of the runs on fluorescence. Again, in Fig. 6, are plotted two runs taken one immediately after the other under conditions identical except for the temperature of the furnace. In the case of run 17 at 475°, the first

type of ionization is so intense as to completely mask the second whereas in run 18 at 25° it is barely detectable.

The other curves obtained were similar to those shown. A summary

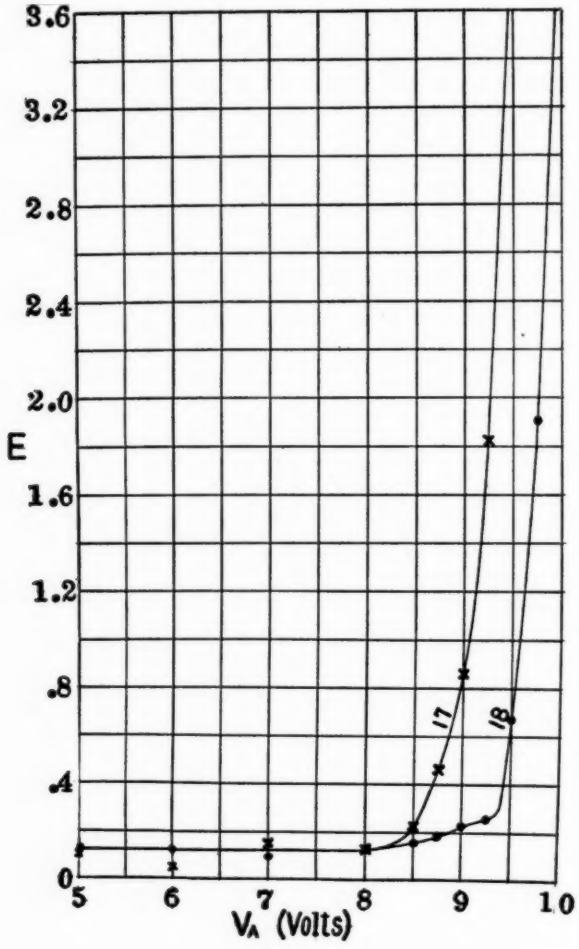

Fig. 6.

of results is given in Table II. The same uncertainty applies to the velocity distribution correction as in the former runs.

where

p = pressure in mm. Hg.;
T = centigrade temperature of apparatus;
G = current to gauze in amperes $\times 10^{-9}$.

TABLE II.

Run.	p.	T.	G.	Corrected Breaks.		
				b.	c.	$c-b$.
12	.01	430°	38–15	8.6	10.2	1.6
13	.01	475°	9–2	8.5	10.2	1.7
14	.032	476°	1.8–2.6	8.7?	——	
15	.032	515°	3.7±	8.9	10.3	1.4
16	.032	475°	5.5	9.3	10.5	1.2
17	.032	475°	3.5	8.5	——	
18	.032	25°	4.5–4	8.4	9.6	1.2
Average omitting doubtful values.....				8.7	10.16	1.42
Average including b, c, and b', c' from runs 1–11				8.0±0.1	9.4±0.1	1.47±.045

Discussion of Results.

The final values at which we arrive, therefore, are 8.0 ± 0.1 volts for ionization of an iodine atom and 9.4 ± 0.1 for ionization of the molecule where uncertainties not taken care of by the calculated probable error may probably reduce the accuracy of these values considerably. The fact that the values in runs 12 to 18 are consistently larger than in runs 1 to 11 emphasizes the possibility of some constant error. Due consideration of the various doubtful factors leads to the conclusion that 8.0 ± 0.5 and 9.4 ± 0.5 would roughly represent the accuracy of our results. The value 9.4 ± 0.5 for molecular iodine agrees within the limits of experimental error with 10.1 ± 0.5 found by Mohler and Foote.[1] The ionizing potential of atomic iodine has not been measured before.

However uncertain may be the determination of absolute values of the above potentials, the difference between them is definitely given. By averaging the values of $c - b$ and $c' - b'$ for runs 1 to 11 and $c - b$ for runs 12 to 18 we get the value 1.47 ± .045. Now the heat of dissociation of iodine vapor is about 35,000 calories per gram molecule[2] which corresponds to 1.52 volts per molecule. The natural inference drawn from this close agreement is that ionization of molecular iodine is accompanied by dissociation. This is predicted by Bohr's theory for hydrogen and has apparently been found experimentally by Mohler and Foote[3] and by Franck, Knipping and Krüger.[4] The latter authors, however, also attribute one of their effects to ionization without dissociation, the occurrence of which in iodine was not observed. Due to the difficulty

[1] Loc. cit.

[2] Starck & Bodenstein, loc. cit.
Bjerrum, Zs. Physikal. Ch., 81, p. 281, 1912.

[3] F. L. Mohler and P. D. Foote, J. Optical Soc. Am., IV, p. 49, 1920.

[4] Franck, Knipping and Krüger, Ber. d. D. Phys. Ges., 21, p. 728, 1919.

in getting thermal dissociation of hydrogen, the methods of distinguishing effects of atomic and molecular ionization are necessarily indirect and there has as yet been no work done on this question for other diatomic gases.

PART III. GENERAL DISCUSSION.

The results of the foregoing investigations are of interest in that they afford evidence regarding possible modes of ionization and of photochemical action.

It has been suspected that ionization may, under suitable conditions, be accomplished in two stages, the first being the removal of an electron to a less stable position by the absorption of the appropriate amount of radiant energy of proper frequency, and the second being the further complete removal of this electron by a collision. This method of ionization would account for the ionization which has been observed at the resonance potential in low voltage arcs, and has been indirectly shown to be effective in the ionization of helium.[1] It appears to be proven directly in the present experiments.

It is generally assumed that the primary effect of light in photochemical reactions is to displace or "loosen" an electron of the activated molecule so as to render it physically less stable, or chemically more active. There is some doubt regarding the nature of this "loosening." Experimental evidence, and also the known conditions of ionization, render it unlikely that this loosening consists in complete ionization in the great majority of cases. On the other hand, partial ionization or displacement seems capable of accounting for the so-called "primary" photochemical actions; and such displacement with reëmission of radiant energy following the chemical reaction seems to account for the "secondary" actions.[2] The present investigation of fluorescing iodine may be thought of as a measurement of the degree of loosening of the electrons by light, and such loosening has been found to be given, at least approximately, by the quantum relation. Apparently the effect of the light is not, in this case at least, the dissociation of some of the molecules—an explanation of photochemical action recently suggested by Nernst.

The results of the present investigation are evidently in accord with the viewpoint recently suggested by Perrin,[3] whereby quanta of radiant energy are emitted or absorbed in all chemical reactions.

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[1] K. T. Compton, Phil. Mag. in print.
K. T. Compton, E. G. Lilly, and P. S. Olmstead, PHYS. REV. in print.

[2] Bodenstein, Zeitsch. Phys. Chem., 85, p. 329, 1913.

[3] Ann. de Phys., 11, p. 5, 1919.

Note added with the proof.—Clifton G. Found has published data on the ionizing potential of iodine, among other gasses, in a recent number of the PHYSICAL REVIEW (Vol. 16, p. 41, 1920). He interpreted his results as due to a *single* type of ionization, drawing an average smooth curve through his plotted points, and concluding that the ionizing potential is $(25)^{2/3}$ or 8.5 volts. A closer examination of his results shows, however, that there are *two* break points, a pronounced one at $(31)^{2/3}$ or 9.8 volts and another, less sharply defined, at about $(24)^{2/3}$ or 8.3 volts. It is significant that these agree, within the limits of probable error, with the ionization potentials of molecular and atomic iodine found by us.

THE ABSORPTION OF SOUND BY RIGID WALLS.

BY PAUL E. SABINE.

SYNOPSIS.

Absorption assumed to be due to porosity, the absorbing walls being so massive that flexural yielding is presumably negligible. Upon this assumption, *Rayleigh's theory* indicates that the absorption by such a wall is very nearly proportional to the square root of the frequency of the sound.

Absorption is approximately a linear function of the square root of the frequency, as shown by experiments for a range of frequencies between 64 and 4096 periods per second, but the absorption frequency curve does not pass through the origin, and at higher frequencies the absorption is greater than can be accounted for by porosity alone.

Selective transmission of a frequency whose wave-length in the wall is twice the thickness gives a possible explanation. Absorption experiments at still higher frequencies are desirable.

PROF. WALLACE C. SABINE has shown[1] that the rate of decay of sound in a room may be expressed by the equation

$$\frac{dI}{dt} = -AI, \tag{1}$$

A being a function of the dimensions and shape of the room, and of the absorbing properties of the walls, and the various exposed surface in the room. If we consider simply the absorption of the bounding surface of an empty room then the value of A is given by the equation

$$A = \frac{va}{sp}, \tag{2}$$

in which v is the velocity of sound, a is the total absorbing power of the room, s the total surface and p the mean free path of the sound between reflections. The absorbing power a is the sum $a_1s_1 + a_2s_2 +$ etc., a_1, a_2, etc., being the ordinary absorption coefficients of the bounding surfaces s_1, s_2, etc., respectively. The values of these absorption coefficients for materials ordinarily used in wall and ceiling construction are of fundamental importance practically in architectural acoustics. They have been determined with great care for a large number of materials over the entire range of frequencies used in speech and music, and are given in various papers published by Professor Sabine.[2]

[1] Architectural Acoustics, Part I.

[2] Proc. Am. Acad. Sci., Vol. LXII., No. 2, 1906; The Brickbuilder (Boston), Jan., 1914.

Qualitatively, the theory of sound absorption is simple. The dissipative forces through which the sound energy is converted into heat are introduced in two ways. The yielding of reflecting surface as a whole, or in large units of area under the alternating pressures of the sound wave calls into play damping forces, which dissipate the sound energy. In the case of porous surfaces, the viscosity of the air and the transfer of the heat of compression from the air to the walls of the minute channels formed by the pores also become effective. It is probable that in most cases both of these effects are present, so that while qualitatively simple, the problem in general does not admit of quantitative theoretical treatment. For example, it would seem obvious that in heavy felt and fabrics, porosity is the predominating factor, yet the curves for the absorption coefficient of such materials plotted as a function of the frequency of the sound show maxima and minima, indicating that resonant yielding of the material as a whole plays a part. The separation of the two factors in any particular case is difficult. Making certain simplifying assumptions, Lord Rayleigh,[1] following the method of Kirchoff,[2] developed an expression for the absorption of a porous non-yielding surface. He assumed that the depth of the pore channels is small compared with the wavelength, but large relative to the diameter, and that the flow into the channels, is sensibly equal to that across them at a certain short distance from the surface. The value for a, defined as above, is given by the equation

$$a = \frac{4M}{2M^2 + 2M + 1}, \tag{3}$$

where M is defined as equal to

$$\frac{2(1+g)\sqrt{\mu'\gamma}}{r\sqrt{n}},$$

in which g is the ratio of the perforated to the unperforated area of the porous surface, μ' the kinematic viscosity of the gas, μ/ρ°, γ the ratio of the specific heats of the gas, r the radius of the pores considered as cylindrical, and n is $2\pi \times$ the frequency of vibration. It should be noted that the absorption coefficient, as defined, includes the entire fraction of the incident energy that is not reflected.

Putting in reasonable values for g and r, M^2 is found to have values much greater than unity for the frequencies of the ordinary musical tones, so that, neglecting unity in the denominator (3) may be written

$$a = \frac{2}{M+1} = \frac{2r\sqrt{n}}{(1+g)\sqrt{\mu'\gamma} + r\sqrt{n}}. \tag{4}$$

[1] Theory of Sound, Vol. II., p. 328.

[2] Pogg. Ann., CXXXIV., p. 177, 1868.

Lord Rayleigh points out that equation (4) holds good only in case the radius of the pores is sufficiently small to allow free exchange of heat between the air and the sides of the channels and estimates that if r is much greater than .01 cm. the equation does not hold.

The flexural yielding of massive masonry is clearly a negligible factor in the absorption of sound. Such walls ought to satisfy approximately the assumptions involved in the derivation of equation (4). The following table gives the absorption coefficients for 18″ walls of hard brick set

	Frequency.		
	1	2	3
64.....	.021		
128.....	.023	.0092	.0079
256.....	.026	.0097	.0084
512.....	.032	.0120	.0104
1024.....	.040	.0150	.0144
2048.....	.052	.0190	.0174
4096.....	.070	.028	.025

in mortar. In colum 1 are the values given by Prof. Sabine,[1] for unpainted brick surface, column 3 is for a surface of gypsum plaster with a so-called "putty finish" taken about three months after being put directly on to an 18 in. brick wall and column 2 is for the same surface a year afterwards. The values for columns 2 and 3 were obtained in this Laboratory. These results are plotted as ordinates in the accompanying figure, with the square roots of the frequencies as abscissæ. The increase in absorption of the plastered wall with time is probably due to an increase in the porosity of the surface, as the walls become more thoroughly dry. It has been frequently noted that the reverberation in empty rooms with newly plastered walls is decidedly greater than in the same rooms later on. Obviously the curves may be represented by an equation of the form

$$a = K_0 + K_1(f)^{1/2} + K_2(f).$$

For curve 3, K_0, K_1 and K_2 have the values .007, .00013, and .0000026 respectively with corresponding values for curves 1 and 2.

Turning now to equation (4) and expanding in a power series, the value of a is given by the expression

$$a = K_1'(f)^{1/2} - K_2'n + K_3'(f)^{3/2} - \text{etc.}$$

Since for frequencies not greater than 4096 p.p.s. M is large in equation (4) in comparison with 1, the sum of the terms after the second will be small in comparison with the second term, so that the sum of terms after

[1] Proc. Am. Acad. Sci., Vol. XLII., No. 2, 1906.

the first will be intrinsically negative. Plainly the theoretical curve will be concave toward the axis of abscissæ.

A comparison may now be made between the results of experiment and Rayleigh's theory.

(*a*) The fact that the experimental curves do not pass through the origin as does the theoretical curve indicates that not all the loss of energy in reflection is accounted for by viscosity and heat conduction.

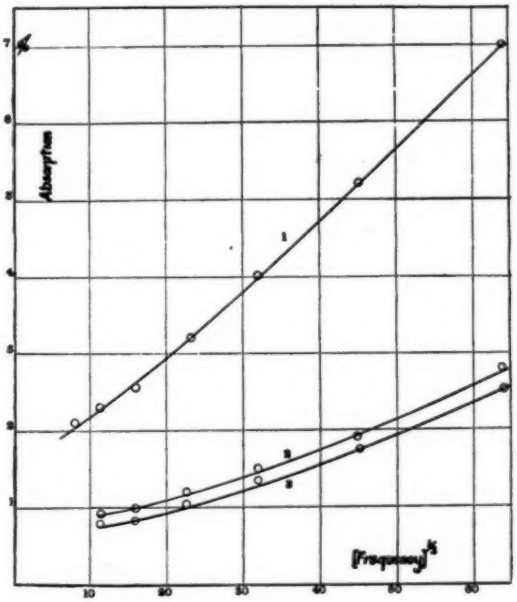

Fig. 1.

The refraction of sound into the wall considered as a second medium of different density and compressibility, may be shown to be negligible in comparison with the absorption at zero frequency as determined by extrapolation of the experimental curves. Computation based on the relative velocities of sound in the air and in the wall shows that the transmitted energy is of the order of .00025 times the incident energy, if the wall be considered simply as a continuous medium, transmitting a portion of the incident energy, and reflecting the rest.

(*b*) The experimental and the theoretical curves have curvatures of opposite signs. If the whole absorption of the wall is to be accounted for by the porosity the value of the absorption should approach a limit, as the frequency is increased whereas the experimental curves do not show this tendency over the range of frequencies employed.

It appears then that the dissipation of sound energy in a room with

massive walls can not be wholly accounted for by the porosity of the walls. In the analogous case in light, the shape of the experimental curves would be explained by the assumption of an absorption band in the region of the higher frequencies due to the natural free period of the electrons in the absorbing medium.

In the case under consideration, such a natural frequency may be supposed to be present because of the limited thickness of the wall. Under the alternating pressure of the incident sound wave, a compressional wave is excited in the wall, which will travel with a velocity determined only by the density and the compressibility of the wall material. When the frequency of the sound is such that the thickness of the wall is half the wave-length of the transmitted sound, the inner and the outer wall surfaces become the loops of the stationary wave set up by internal reflection from these surfaces, and the wall will exhibit selective transmission for this frequency. Chladni gives the velocity of sound in masonry as approximately 12,000 ft. per sec. The frequency natural to a wall 18 in. thick is approximately 4,000 p.p.'s, which is a little less than the highest frequency in the experiments. Some experiments conducted in this Laboratory in connection with another problem indicate that the response of an extremely massive body to its own natural vibration frequency is probably sufficiently large to show an appreciable effect in the absorption of sound by the body. It would consequently be of great interest to carry the absorption measurements to still higher frequencies but unfortunately sources of sound of determinable rates of emission are not yet available for such an extension. Moreover, the results by the reverberation method would be in considerable doubt since the response of the ear to very high frequencies is far from possessing the uniformity which it possesses for lower tones.

In conclusion, it may be said that although the Rayleigh formula does not completely account for the experimental results, yet the absorption of walls so thick that flexural yielding does not occur, may be approximately represented as a linear function of the square root of the frequency, over a considerable range of frequencies.

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ON THE THEORY OF POWELL'S BANDS AND THE GROUP-VELOCITY IN DISPERSIVE MEDIA.

By Nihal Karan Sethi.

Synopsis.

Powell's Bands: Observations with liquid mixtures of variable refractive index.—A description is given of the changes in the position, width and degree of visibility of the bands seen in the spectrum when a flat-sided cell containing liquid of which the refractive index is gradually varied is placed behind the prism on the table of a spectroscope, a transparent plate of glass being immersed in the cell so as to cover half the aperture. The liquid chosen for the experiment was a mixture of CS_2 and benzene of which the proportions could be altered in any desired manner. Special attention is paid to the stage at which the position of the plate in the cell has to be reversed in order that the bands might continue to be visible.

Powell's Bands: Condition of visibility.—Mascart's and Schuster's statements on this point in their treatises are criticized, and it is shown that the side of the cell on which the plate should be immersed is determined not by the relation between the refractive indices of the liquid and the plate but by the group-velocities in the two media. Owing to the highly dispersive nature of the liquid employed in the experiments, the position of the plate has on this account to be changed from one side to the other at a stage at which the refractive index of the liquid is still lower than that of the plate for the whole of the visible spectrum.

Powell's Bands: Relation to Laminar Diffraction.—Spectroscopic analysis of the laminar diffraction either of the Fraunhofer or the Fresnel type formed by the plate immersed in the liquid gives oblique interference lines, photographs of which are given. Their number and the positions at which they cross the spectrum are identical with those of Powell's bands and their inclination to the direction of the spectrum indicates at once the side on which the plate should be immersed for observation of Powell's bands and the degree of visibility of these bands. The visibility is maximum when the interference lines are inclined at 45° to the length of the spectrum.

Group-velocity of Light: Direct determination of the position of its identity in two media.—This is rendered possible by the fact that the oblique interference lines mentioned above curve round and become inclined in the opposite direction at this position as shown in the photographs given.

Determination of Refractive Indices and Dispersive Powers.—As the oblique interference-lines in the spectrum of laminar diffraction are seen clearly and sharply-defined irrespective of the thickness of the plate or the aperture of the telescope within wide limits, it is suggested that they may be used in the preference to Talbot's and Powell's bands for such determinations.

1. Introduction.

Powell[1] observed a remarkable system of interference bands when a hollow prism containing liquid was used to form a spectrum and

[1] Baden Powell, Phil. Trans., 1848, Pt. II., page 213.

a transparent plate with its edge parallel to the refracting edge of the prism was immersed inside the liquid so as to cover half the effective aperture of the beam passing through it. A convenient method of studying these bands was suggested by Stokes.[1] An ordinary spectroscope with glass prism may be used and a flat-sided cell containing the liquid chosen is put on the table of the instrument. The plate is then immersed inside this cell so as to cover half the aperture, leaving the other half covered by the liquid only. Whether the bands are visible or not in any case depends on the side of the beam which is covered by the plate. Mascart and Schuster state in their treatises[2] that it is necessary, if the bands are to be seen, to place the plate on the thicker side of the prism if the refractive index of the liquid is greater than that of the plate, and to put it on the thinner side if the refractive index is less. The present author had occasion recently to make some observations of Powell's bands with plates immersed in liquid mixtures of varying composition, from which it would appear that the foregoing statement is not correct and that the actual condition for the visibility of the bands should be stated somewhat differently. The side on which the plate should be placed is determined by the relation between the *group-velocities* of light in the two media and not by their refractive indices as stated by Mascart and Schuster. When the group-velocity is less in the liquid than in the plate, the plate should be placed on the thicker side of the prism and when greater the plate should be placed on the thinner side. In the case of a plate immersed in a highly dispersive liquid of nearly the same refractive index, *e.g.*, a plate of glass immersed in a mixture of carbon disulphide and benzene it is possible to have the group-velocity in the liquid to be less than that in the plate, though the refractive index of the latter may be greater throughout the visible spectrum. In such a case, the position of the plate for visibility of the bands would actually be the reverse of that necessary if the differences of refractive indices had been the criterion. It is proposed in the present paper to describe some experiments illustrative of this aspect of the theory of Powell's bands and to explain a simple method by which the identity or difference between the group-velocities in the two media may be ascertained by direct observation without requiring a knowledge of their dispersive powers.

[1] Stokes, Phil. Trans., 1848, Pt. II., page 227, and Math. and Phys. Papers, Vol. II., page 14.

[2] Mascart, Traite D'Optique, Tome premier, page 474.
Schuster, Theory of Optics, second edition, page 119.

2. Theory of Powell's Bands.

The condition for the visibility of Powell's bands may be found by applying in their case a train of argument similar to that which has been used by Professor Schuster himself[1] to explain the formation of Talbot's bands. When impulses of white light pass through a prism, they are dispersed and the impulses passing through the thicker portion of the prism are retarded more than those passing through the thinner. Accordingly, at the focus of a lens placed to receive the beam, the impulses from the thin end of the prism will be the first to arrive and will be followed in succession by those that have passed through increasingly thicker portions of the prism. These impulses as such cannot interfere because they do not arrive at the *same time* but if it is so arranged that the impulses coming through the two halves of the prism arrive in pairs *simultaneously*, it is possible to produce interference effects. This can be done either by a relative retardation of those impulses which have travelled through the thinner portion of the prism or by a relative acceleration of those that have passed through the thicker. If on the contrary the reverse of this is done, the interval between the arrival of the impulses will be further augmented and no interference will be possible. In the case of Powell's bands the relative retardation or acceleration is produced by means of covering half the aperture by a plate immersed in a liquid. It is clear that the plate will retard the impulses passing through it when the velocity with which they travel through it is less than that with which they travel through the liquid. The impulses travel through the liquid and plate with the respective group-velocities in the media which depend not only on their refractive indices but also on their dispersive powers. If the dispersive power of the liquid is greater than that of the plate, it is possible to have the group-velocity in the liquid less than that in the plate even when the refractive index of the latter is higher. In such a case, in spite of its higher refractive index, the plate will not act as a retarding plate but will result in a relative acceleration of the impulses passing through it. Consequently it will have to be put on the thicker side of the prism. Thus it is clear that the correct condition for the visibility of the bands is that stated above, namely that so long as the group-velocity of light in the plate is less than in the liquid, the plate must be introduced on the thinner side of the prism. When it is greater, the plate must be introduced on the thicker side. The transition from one case to the other takes place when the group-velocities in the two media are equal.

[1] Schuster, Phil. Mag., Vol. VII., Jan., 1904, page 1. See also R. W. Wood, Physical Optics, second edition, pp. 259 and 657.

3. OBSERVATIONS OF POWELL'S BANDS WITH LIQUID MIXTURES.

The foregoing remarks are most conveniently illustrated by using a mixture of carbon disulphide and benzene as the liquid in the cell. The mixture has a high dispersive power and by altering the proportions of the constituents the refractive index may be adjusted as desired. The state of the mixture as regards its refractive index can be very simply ascertained by looking at the incandescent filament of an electric bulb obliquely through the edge of the plate while immersed in the cell. The position of the spectrum formed by the edge of the plate with reference to the filament gives the necessary indications.

In some observations made by the author, the cell containing the liquid was placed between the prism and the observing telescope of a spectrometer. The experiment was begun with carbon disulphide alone and very sharp and narrow bands were observed throughout the spectrum when a thin glass plate was immersed in the cell on the thicker side of the prism. As the refractive index of the liquid was lowered, the bands increased in width and a thicker plate (about 5 mm.) had to be used in order to keep them of a convenient size. This plate was cut from an ordinary good quality mirror glass. When the refractive indices of the plate and the mixture became more nearly equal, even the thickness of this plate proved to be less than the "best." As it was not convenient to use thicker plates, the device of cutting down the aperture of the beam passing through the cell was adopted. Nothing special happened when the refractive indices for the red, yellow, green, blue and even the violet were equalized in succession, except that very narrow apertures down to a slit about 1 mm. in width had to be employed to keep the bands at maximum visibility. Although the refractive index of the liquid had now becomes less than that for the plate almost throughout the visible spectrum, the bands remained as clear and distinct as ever with the plate still on the thicker side of the prism. The width of the bands, however, did not remain uniform, those towards the red end being wider apart. With further diminution of the refractive index, the bands in the red became very broad indeed and gradually decreased in visibility and ultimately disappeared altogether, and this was followed by the disappearance of the bands in the yellow and the green. At this stage, on introducing the plate on the other side, broad bands could be seen in the yellow and red regions, becoming narrower and more distinct towards the red side, thus showing that the same combination of the liquid and the plate gives bands in one part of the spectrum with the plate on the thinner side of the prism (Fig. 1) and in another part with the plate on the thicker side (Fig. 2). By further addition of benzene, the

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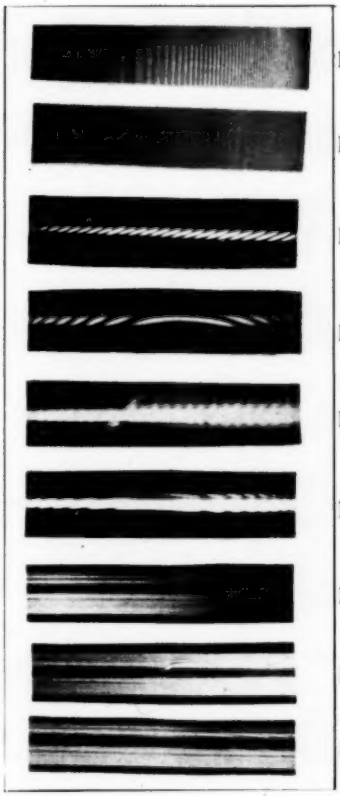

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

Fig. 9.

N. K. SETHI.

point of zero visibility of the bands separating these two parts of the spectrum could be shifted further and further towards the violet end until finally the bands in the visible spectrum could be seen only with the plate on the thinner side of the prism.

4. Relation between Laminar Diffraction and Powell's Bands.

A study (by the method of spectroscopic analysis) of the laminary diffraction pattern produced by the plate while immersed in the liquid is very instructive and serves clearly to demonstrate that the group-velocities in the plate and the liquid are identical at the point of zero visibility of Powell's bands in the spectrum. For this purpose, the laminar diffraction pattern either of the Fraunhofer or the Fresnel type may be used. White light from a narrow slit is allowed to fall on the cell containing the plate and the liquid, the slit being parallel to the edge of the plate. The plate should be adjusted so as to be quite normal to the light by tilting it about its edge till the shadow of this appears as a fine sharp line. If the Fresnel pattern is to be observed, all that is necessary is that the slit of a direct-vision spectroscope be placed across the shadow of the edge at a distance of about 15 or 20 cm. from the plate. If the Fraunhofer pattern is to be observed, a lens has to be added to the above arrangement in order to focus the image of the first slit on the slit of the spectroscope. The aperture of the lens should also be limited so as to make the central band sufficiently wide. The edge of the plate should bisect this aperture.

Figs. 3, 4, 5 and 6 show photographs of the spectrum of the Fraunhofer diffraction pattern in different cases. Figs. 3 and 5 are respectively dense and light prints from the same negative taken when the refractive indices of the plate and the liquid were equal for the blue-violet region of the spectrum. It will be noticed that in the deeper print (Fig. 3) a series of interference bands are seen running obliquely through the spectrum but there is nothing which specially distinguishes the position of equality of refractive indices,[1] the bands running in the same direction throughout. The lighter print (Fig. 5) shows the fainter bands above and below the central band in which a certain asymmetry of illumination can be seen. This is due to a slight prismatic action of the edge of the plate and it can be seen that these bands become reversed at the wave-length in the spectrum at which the refractive indices are equal. Figs. 4 and 6 were taken when the refractive index of the liquid was lower than that of the plate throughout the visible spectrum. It will be seen that

[1] Except a certain increase in the intensity of the band cutting obliquely through the spectrum at this point which is however not very strikingly shown in the print.

in this case the bands are much wider apart and in proceeding along the spectrum they gradually change their inclination, curve round and become inclined in the opposite direction.

Figs. 7, 8 and 9 show the spectrum of the Fresnel pattern of which Figs. 7 and 8 refer to the same condition of the liquid as with Figs. 3 and 5. In Fig. 8, the plate was purposely kept a little tilted about its edge and it shows the asymmetry of illumination on the two sides more clearly. Fig. 9 was obtained in circumstances similar to those of Fig. 4 and it will be seen that as in that case the dark interference bands appearing in the center change their inclination and curve round to the opposite direction.

It was found experimentally that the position of the curved band in Figs. 4 and 9 corresponded exactly with the point in the spectrum at which the visibility of Powell's bands is zero. The fact that the direction of the spectrum is tangential to the interference lines in the pattern at this point shows clearly that the phase change produced by the plate measured in radians for the various wave-lengths in this neighborhood is constant. If μ_g and μ_l are the refractive indices of the plate and the liquid respectively, λ the wave-length of light and e the thickness of the plate, this condition gives

$$\frac{2\pi e}{\lambda}(\mu_g - \mu_l) = \text{constant},$$

i.e.,

$$\frac{d}{d\lambda}\left(\frac{\mu_g - \mu_l}{\lambda}\right) = 0$$

or

$$\mu_g - \lambda\frac{d\mu_g}{d\lambda} = \mu_l - \lambda\frac{d\lambda_l}{d\lambda}.$$

which on transformation in terms of the wave-velocities readily gives

$$V_g - \lambda\frac{dN_g}{d\lambda} = V_l - \lambda\frac{dN_l}{d\lambda}.$$

The expressions on the two sides of this equation represent the group-velocities in the plate and the liquid respectively. Thus the curved band marks the position in the spectrum at which the group-velocities in the two media are equal to each other.

That the interference lines appearing in the spectrum of the diffraction pattern curve round and reverse their inclination beyond a certain point in the spectrum obviously stands in intimate relation with the fact that the position of the plate has to be reversed in passing from one side of this point in the spectrum to the other side in order that Powell's

bands might continue to be visible. There is in fact a definite quantitative relation between the obliquity of these interference lines and the degree of visibility of Powell's bands. It may be readily shown that the maximum visibility corresponds to an inclination of 45° to the length of the spectrum. $\mathrm{Tan}^{-1}\,0$ and $\mathrm{Tan}^{-1}\,2$ correspond to zero visibility of Powell's bands and mark the extreme limits between which they are visible.[1]

It may be remarked in conclusion that the determination of refractive indices and dispersive powers for whcih Talbot's and Powell's bands have been used[2] could no doubt be made more conveniently by using the spectrum of laminar diffraction pattern preferably of the Fraunhofer type. The oblique bands found in this way cut the spectrum exactly at the same points as the corresponding Talbot's or Powell's bands and they are generally easier to see. There is no question of having the "best thickness" of the plate and no necessity to limit the aperture of the observing telescope in order to see the bands clearly.

The experimental work was carried out in the Laboratory of the Indian Association for the Cultivation of Science and the writer desires to express his gratefulness to Prof. C. V. Raman for his very helpful interest in the work.

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[1] The distance of the diffraction pattern from the lens forming it is taken as equal to the focal length of the spectrometer telescope.

[2] A very useful bibliography on this point is given in a paper by T. E. Doubt in Phys. Rev., Vol. X., series II., page 332, Oct. 1917.

ON THE X-RAY SPECTRA OF TUNGSTEN.[1]

BY WILLIAM DUANE AND R. A. PATTERSON.

SYNOPSIS.

Critical Absorption and Emission Wave-lengths in K and L Series.—This paper describes accurate measurements of the critical absorption wave-lengths associated with the K and the L series, and also of the wave-lengths of most of the emission lines in the L series. The measurements were made by means of a new ionization spectrometer, similar to the one described in the PHYSICAL REVIEW for Dec., 1917, at page 624. A high tension storage battery supplied the current through the X-ray tube, the voltage and current being kept constant by the procedure indicated in the reference. To eliminate errors due to the penetration of the rays into the crystal and to lack of exact adjustment between the axis of rotation of the crystal and the *effective* reflecting plane, etc., the authors employed the third method mentioned in the article referred to, above. In this method two slits between the X-ray tube and the spectrometer define the width of the beam of X-rays that strikes the crystal, and the slit in front of the ionization chamber has sufficient breadth to allow the entire reflected beam to enter the chamber. With this arrangement of slits the angle through which the crystal turns (not the angle made by the *reflected* beam of rays with the zero of the instrument) measures the glancing angle that is used in the formula to calculate the wave-length.

Mean Values of the Wave-lengths Measured in Spectra of the 1st, 2d and 3d Orders.—The following table contains the weighted mean values of the wave-lengths obtained from measurements in spectra of the 1st, 2d and 3d orders, together with an estimate of the precision of the measurements. To estimate the *absolute* accuracy of the data we must take into account the errors in the value of the grating constant of the calcite crystal used. These add up to about 0.07 per cent. In the text the values of the emission wave-lengths obtained by this ionization method are compared with those measurements of the same lines by photographic methods in which special procedures have been employed to minimize the effects of the above mentioned errors.

X-Ray Spectra of Tungsten.

Grating Constant for Calcite $2a = (6.056 \pm .004) \times 10^{-8}$ cm.

Critical Absorption Wave-Lengths, $\lambda \times 10^8$ cm.

Ka	La_1	La_2	La_3	
.17806 ± 7	1.2136 ± 1	1.0726 ± 5	1.024 ± 3	
Emission Wave-Lengths, $\lambda \times 10^8$ cm.				
$K\alpha_2$	$K\alpha_1$	$K\beta$	$K\gamma$	
.21341 ± 3	.20860 ± 4	.18420 ± 3	.17901 ± 6	
Ll	$L\alpha_2$	$L\alpha_1$	$L\eta$	
1.6756 ± 10	1.4839 ± 3	1.47306 ± 11	1.4176 ± 7	
$L\beta_4$	$L\beta_1$	$L\beta_3$	$L\beta_2$	$L\beta_5$
1.2985 ± 4	1.27892 ± 9	1.2601 ± 3	1.24193 ± 12	1.2040 ± 7
$L\gamma_1$	$L\gamma_2$	$L\gamma_3$	$L\gamma_4$	
1.09608 ± 7	1.0655 ± 4	1.0596 ± 3	1.0261 ± 6	

[1] A paper presented to the American Physical Society at its New York meeting, Feb. 28, 1920.

The K emission wave-lengths have been taken from a paper by Dr. Stenström and one of the authors.

The Relative Intensity of the Lines.—The ionization spectrometer furnishes the best method of estimating the relative intensity, the relative breadth, etc., of emission and absorption lines, provided that they are so near together that the effect of absorption by the tube, etc., may be neglected or corrected for. The numerous curves in the text give a good idea of the relative intensity, etc., of the lines.

The Differences between the K and L Absorption Frequencies Equal the Kα Emission Frequencies in Each Case to Within the Errors of Measurement.—The object of the research has been to obtain accurate values of both the absorption and the emission wave-lengths measured under the same experimental conditions. This becomes particularly important in testing theoretical laws and relations. According to the theory of the mechanism of radiation based on the Rutherford-Bohr atomic model the K critical absorption frequency should be complex, if, as Sommerfeld assumes, some atoms contain elliptic orbits and other atoms of the same chemical element contain circular orbits. Further the difference between the *average* K critical absorption frequency and one of the L critical absorption frequencies should not exactly equal the frequency of one of the Kα emission lines. As a matter of fact the authors have not observed a doubling of the K absorption frequency, and their new measurements verify the results obtained last year by Duane and Shimizu.[1] The difference between the K absorption frequency and one of the L absorption frequencies equals the frequency of one of the Kα emission lines in each case to within the errors of measurement. Hence, if the effect due to different kinds of tungsten atoms exists at all, it is too small to be detected, at least for chemical elements of high atomic numbers.

Test of Sommerfeld's Formula for the Frequency Interval of the L Doublet.—A Sommerfeld[2] has deduced from Bohr's theory an expression for the frequency interval of the L series doublet by making an interesting application of one of the equations in the quantum theory, which enables him to calculate the eccentricity of an elliptic orbit. The expression contains one undetermined constant, to which he gives the value 3.63. This value he obtains by using the published wave-lengths of the lines in the L series of a great many chemical elements. Although there is some difficulty in giving a physical interpretation to the theory, yet, when one substitutes the constant in the formula, one obtains the frequency difference of the L series doublet in the tungsten spectrum to within less than one per cent. of the value we found by experiment.

Object.—The object of the research reported in this paper has been to measure both the critical absorption and the emission wave-lengths associated with the K and the L series of tungsten. Values of these absorption and emission wave-lengths measured under the same experimental conditions are not available at present, and, evidently, for the purpose of testing certain relations deduced from theories of the structure of atoms and the mechanism of radiation, such a series of comparable wave-lengths should be obtained.

Apparatus and Method.—In order that the values of the wave-lengths might be as free as possible from errors due to the penetration of the X-rays into the reflecting crystal, and to lack of exact adjustment

[1] PHYSICAL REVIEW, July, 1919, p. 67.

[2] Atombau und Spektrallinien, Chapter 5.

between the axis of rotation of the crystal, the incident beam of rays, the *effective* reflecting plane in the crystal, etc., we have employed a new ionization spectrometer, similar to the one described in detail in the PHYSICAL REVIEW for December, 1917, at page 624. The new instrument does not differ essentially from the old one, but has circular scales that appear to be somewhat more exact. We were able to detect no difference between the readings of the two verniers attached to the crystal table that would give us a perceptible correction for excentricity in the parts of the scale used.

We have adopted the third method of arranging the spectrometer slits mentioned in the article referred to above. A narrow beam of X-rays, defined either by two slits in lead blocks between the X-ray tube and the spectrometer or by one slit and the focal spot on the target, falls on the reflecting crystal. The third slit, that in front of the ionization chamber, has sufficient breadth to allow the entire reflected beam to enter the chamber. The chief advantage of this arrangement lies in the fact that no correction is necessary for the penetration of the rays into the crystal and for the lack of exact adjustments in certain parts of the instrument. By taking readings corresponding to the same spectrum line on both sides of the zero, twice the glancing angle of incidence can be calculated by simply subtracting the angle through which the crystal has been turned from 180°. The angle through which the ionization table has been turned does not enter into the calculation. In those methods of using a spectrometer in which the glancing angle has to be calculated from positions of the reflected beam of rays (photographic methods, for instance) corrections for the above mentioned sources of error must be applied, or else special devices must be employed to eliminate them.

In making a series of measurements the crystal and ionization chamber are rotated through successive angular increments, the chamber always being moved twice as far as the crystal. In each position of the crystal the ionization current is measured. The graphs representing ionization currents as functions of the crystal table angles (see the figures) indicate peaks, corresponding to characteristic emission lines, and sharp drops, corresponding to characteristic absorption lines. To get the double glancing angle of incidence, 2θ, for substitution in the wave-length formula,

$$\lambda = 2a \times 10^{-8} \sin \theta \text{ cm.},$$

we measure from the tips of the peaks or the centers of the drops, as the case may be.

To sum up, the above described arrangement of slits and general

procedure eliminates errors due to the following causes: (*a*) penetration of the rays into the crystal; (*b*) the axis of rotation of the crystal not lying exactly in the effective reflecting plane; (*c*) the center of the incident beam not passing exactly through the axis of rotation and (*d*) certain of the defects in crystal structure.

A further advantage of the ionization method lies in the fact that very good estimates of the relative intensity of spectral lines may be

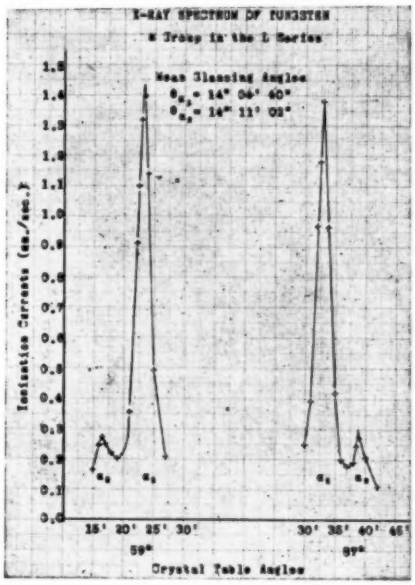

Fig. 1.

obtained, provided that the lines lie so close together that we may neglect, or correct for errors due to changes in the coefficients of absorption and of reflection with wave-length.

For the tungsten emission spectrum we used an X-ray tube of the Coolidge type equipped with a tungsten target. The rays emerged from the tube through a thin glass window blown in a side arm attached to it. This materially reduced the absorption of the relatively soft L series lines. The rays emerging through this window left the target at almost grazing angles. This gave so narrow a source of rays that only one slit was needed to make the incident pencil of rays as narrow as desired.

As in earlier researches a high tension storage battery supplied the current through the X-ray tube, the voltage being kept constant during an experiment by gradually changing a resistance in series with the tube. The usual method of control of the current through the tube enabled

us to maintain the apparatus in a steady state, and to keep the temperature of the target, etc., constant.

We used a lead ionization chamber filled with methyliodide or ethylbromide and provided with a very thin mica window to reduce the absorption of the reflected beam of X-rays as it entered the chamber. A quadrant electrometer measured the ionization currents.

Tungsten L emission Lines.—Thirteen lines in the L series of tungsten have been measured. Figs. 1, 2 and 3 show typical curves platted from actual measurements on the α, β and γ groups of lines respectively. The position of a peak can always be located as between two crystal

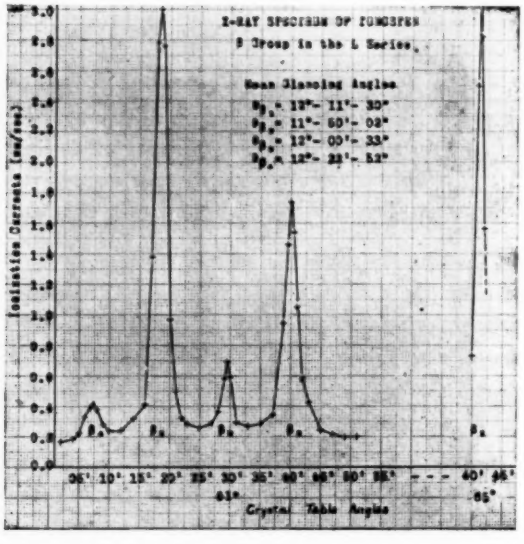

Fig. 2.

angle readings, 30″ of arc apart. Moreover, a good estimate may be made as to how much nearer the actual peak lies to one of these readings than to the other. We believe that, by making several complete series of measurements, we have been able to determine the value of the double glancing angle, 2θ, to within less than 10″ of arc in many cases. This means an error of not more than .01 to .02 of a per cent. in the value of the glancing angle, depending upon its magnitude. The grating space, d, of calcite is known to within about 0.07 of a per cent. No other grating space appears to have been determined as accurately as this. The best determinations of the grating space of calcite lie within a few hundredths of a per cent. of 3.028×10^{-8} cm. We have chosen this value, therefore, to use in calculating our wave-lengths. Hence, taking the grating space of calcite as fixed, we may assume that the relative

values of our wave-lengths are correct to within .01 or .02 of a per cent., according to their magnitudes, in our best experiments.

The lines l, α_1, α_2, η, β_1, β_2, γ_1, and γ_3 have all been measured on both sides of the zero position of the crystal. The glancing angles for β_3, β_4,

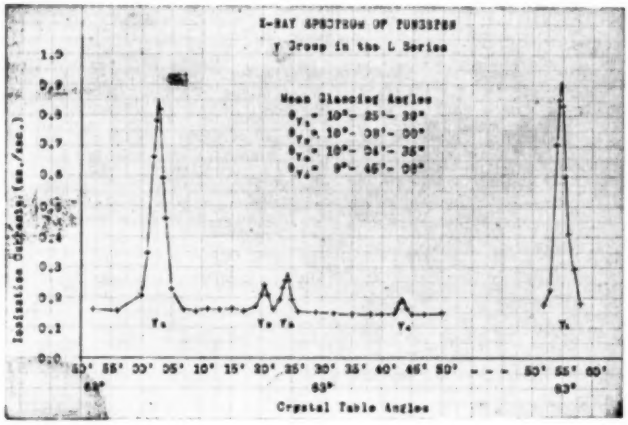

Fig. 3.

β_5, γ_2 and γ_4, however, have been determined by comparison with the glancing angles for neighboring strong lines.

Measurements of the glancing angles for α_1, β_1 and γ_1 have been

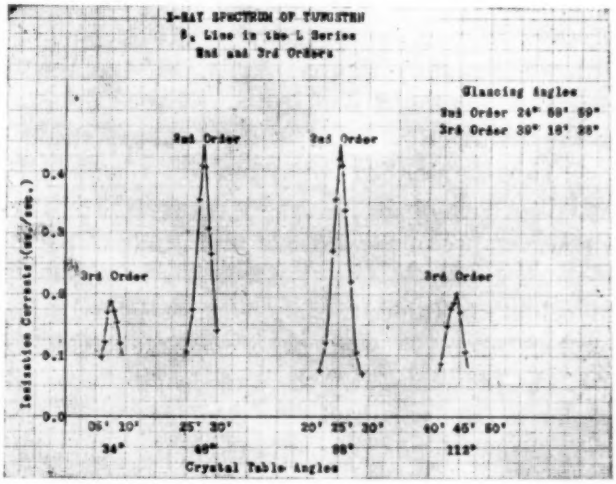

Fig. 4.

made in the first and second order spectra, and for β_1 also in the third order spectrum. Fig. 4 shows the curves obtained for β_1 in the second

and third order spectra. There is a slight indication in the third order spectrum that this line has a close and weaker satellite on its short wave-length side.

Table I. contains the glancing angles and computed wave-lengths for α_1, β_1 and γ_1.

TABLE I.

L Series of X-Rays.

Tungsten.

Grating Constant for Calcite $2d = 6.056 \times 10^{-8}$ cm.

Line.	Order.	Glancing Angle.	Wave-length $\times 10^8$ Cm.
α_1	1	14°–04′–46″	1.47322
α_1	1	14°–04′–39″	1.47303
α_1	2	29°–06′–27″	1.47297
β_1	1	12°–11′–32″	1.27898
β_1	1	12°–11′–34″	1.27904
β_1	1	12°–11′–35″	1.27907
β_1	1	12°–11′–34″	1.27904
β_1	2	24°–58′–59″	1.27886
β_1	3	39°–18′–26″	1.27878
γ_1	1	10°–25′–46″	1.09628
γ_1	1	10°–25′–37″	1.09602
γ_1	2	21°–13′–24″	1.09614
γ_1	2	21°–13′–15″	1.09603

It is interesting to note that the wave-lengths computed from data in higher orders are slightly shorter than those computed from lower orders. Stenström[1] has found similar differences in the case of certain longer wave-lengths which he measured by means of the crystals sugar and gypsum. He has ascribed the differences to a small amount of refraction and dispersion of the X-rays by the crystals. The differences here noted, however, are of the order of magnitude of the experimental errors.

The fourth column in Table II. contains our weighted mean values for the wave-lengths, measured in a number of complete series of experiments. For comparison we have tabulated the wave-lengths recorded by Overn[2] and by Siegbahn[3] in the second and sixth columns respectively. A slight correction, amounting to one thirtieth of one per cent., has been subtracted from the values they give in order to make their wave-lengths correspond to the grating constant for calcite that we use. Columns

[1] Doctor's Dissertation, Lund, 1919.

[2] PHYS. REV., Aug., 1919.

[3] Phil. Mag., Nov., 1919.

three and five contain the respective differences. It appears that the wave-lengths measured by the ionization method agree in most cases with those measured by the photographic method to within the limits of experimental errors. In each of the series of measurements by the photographic method great care was taken by the respective authors to

TABLE II.

L Series of X-Rays. $\lambda \times 10^8$ *cm.*

Tungsten.

Grating Constant for Calcite $2a = 6.056 \times 10^{-8}$ cm.

Line.	Overn.	Difference.	Duane Patterson.	Difference.	Siegbahn.
l.....	....	....	1.6756 ± 10	−.0005	1.67448
α_2.....	1.4834	−.0005	1.4839 ± 3	+.0001	1.48403
α_1.....	1.4726	−.0005	1.47306 ± 11	−.00007	1.47299
η.....	....	....	1.4176 ± 7	−.0004	1.4172
β_4.....	1.2980	−.0005	1.2985 ± 4	−.0002	1.29831
β_1.....	1.2789	.0000	1.27892 ± 9	−.00018	1.27874
β_3.....	1.2594	−.0007	1.2601 ± 3	−.0005	1.25958
β_2.....	1.2430	+.0011	1.24193 ± 12	−.00043	1.24150
β_5.....	1.2017	−.0023	1.2040 ± 7	−.0013	1.2027
γ_1.....	1.0963	+.0002	1.09608 ± 7	−.00092	1.09516
γ_2.....	1.0655	.0000	1.0655 ± 4	.0000	1.06548
γ_3.....	1.0592	−.0004	1.0596 ± 3	−.0003	1.05930
γ_4.....	1.0260	−.0001	1.0261 ± 6	.0000	1.02613

correct for or eliminate the sources of error mentioned above. In particular Siegbahn designed an interesting spectrometer for the express purpose of reducing the errors due to penetration of the X-rays into the crystal, etc., to a minimum.

Overn does not include the lines l and η in his table of wave-lengths. He suggests, however, that the marks on photographic plates corresponding to η may represent the α_1 line in the K series of molybdenum in the second order spectrum. As the lines l and η are of considerable theoretical importance we have tested this point by examining the spectrum in the neighborhood of $K\alpha_1$ for molybdenum in the first order spectrum. We found evidence for both molybdenum $K\alpha_1$ and $K\alpha_2$, but their intensities were less than that of the line we regard as $L\eta$ of tungsten. As the intensity of the second order spectrum is very much less than that of the first order spectrum it is impossible that the peak on our curve should represent molybdenum $K\alpha_1$ in the second order.

Critical Absorption Wave-Lengths.—In general the measurement of critical absorption wave-lengths is more difficult and slightly less accurate than that of emission lines. In order to make such a measurement we usually place a screen containing the chemical element to be investigated

in the path of the incident beam of rays between the X-ray tube and the spectrometer, take a series of readings in the neighborhood of the critical point and draw the corresponding ionization current crystal table angle graphs. Figs. 5, 6 and 7 contain such graphs. Owing to the fact that the absorbing substance absorbs X-rays of longer wave-length than the critical wave-length to a less extent than it does X-rays of shorter wave-length a sharp drop in the curve occurs at the critical point.

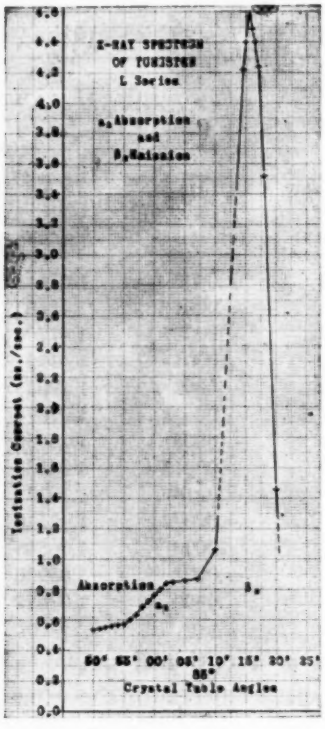

Fig. 5.

In Fig. 5 the absorption drop is due to the target itself, which was so placed that the beam of X-rays that struck the crystal left the target almost grazing its surface. Under these conditions the target absorbs a large part of its own radiation. Fig. 5 clearly shows the relative magnitudes of the emission and absorption spectra. The absorption drop is the largest of the three critical absorptions that have so far been observed in the L series of X-rays. The glancing angle, θ_{a1}, in this case has been estimated by taking the difference between it and the glancing angle, $\theta_{\beta 2}$, of the neighboring emission line.

The other two absorption drops fall so close to emission peaks that good measurements of them can not be made without using an X-ray tube with a target of a different chemical element. Professor D. L. Webster kindly loaned us such a tube, with a molybdenum target. Using it we obtained the curves, represented in Figs. 6 and 7, on both sides of the zero. We estimated the grazing angles, θ_{a2} and θ_{a3}, by measuring from the centers of the corresponding drops.

Fig. 7 contains curves for the K critical absorption of tungsten, obtained in the first, second and third order spectra. We are indebted to Dr. Štenström for his assistance in making these K series measurements.

Table III. contains the glancing angles and computed wave-lengths for the K and L characteristic absorption lines of tungsten.

We wish to call attention to the relative magnitudes of the critical absorption wave-lengths and the wave-lengths of the emission lines.

TABLE III.

Tungsten Absorption Spectrum.

K and L Critical Absorption Wave-Lengths.

Grating Constant for Calcite $2d = 6.056 \times 10^{-8}$ cm.

Absorption.	Order.	Glancing Angle, θ.	Wave-length, $\lambda \times 10^8$ Cm.
Ka.....	1	1°–41′–15″	0.17832
Ka.....	2	3°–22′–19″	0.17810
Ka.....	3	5°–03′–20″	0.17789
			Weighted mean, 0.17806 ± 7
La_1.....	1	11°–33′–37″	1.2136 ± 1
La_2.....	1	10°–12′–07″	1.0726 ± 5
La_3.....	1	9°–44′–05″	1.024 ± 3

The critical absorption wave-length L_{a1} is about $2\frac{1}{3}$ per cent. shorter than that of the β_2 emission line and about .8 of a per cent. longer than

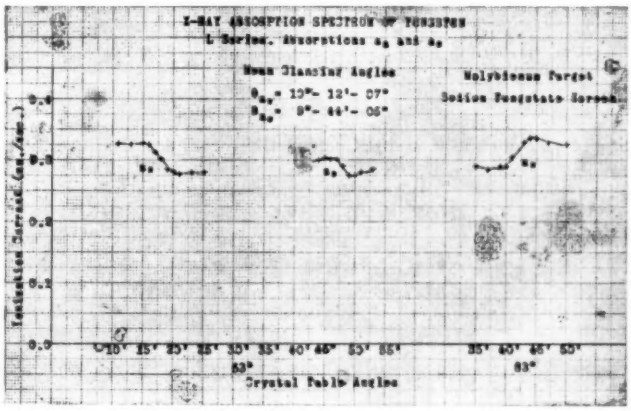

Fig. 6.

that of the β_5 emission line. La_1 lies in the midst of a number of faint lines that have been observed on photographic plates by Dershem, Overn and Siegbahn. La_2 lies between γ_1 and γ_2 (about 0.7 per cent. from γ_2). La_3 lies within a fraction of one per cent. of γ_4, and apparently on its short wave-length side.

Many of the general laws and theoretical equations relating to X-ray spectra are expressed in terms of the frequencies of vibration, the wave-numbers or the ratios of the frequencies to the fundamental Rydberg frequency for heavy atoms. The following table contains the values of ν/ν_∞ calculated from our data. In making these calculations we have used Paschen's value for the wave-number, ν_∞, namely $\nu_\infty = 109{,}737.11 \pm 0.06$, the accuracy of which far exceeds that of any X-ray measurement that can be made at the present time.

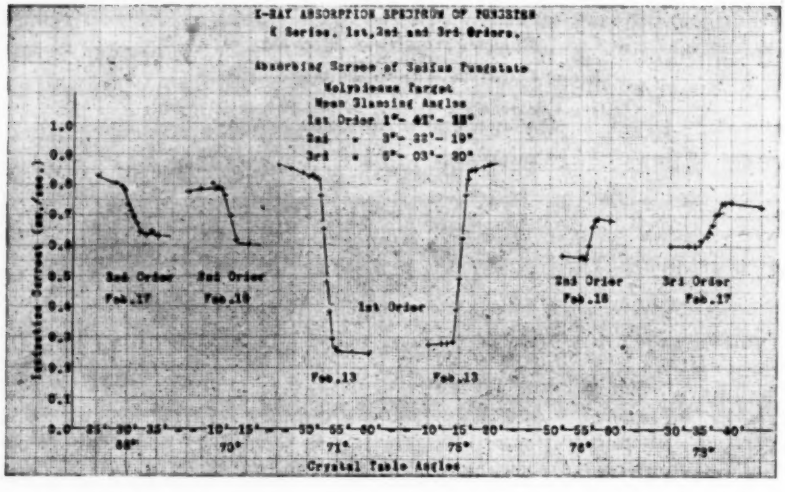

Fig. 7.

TABLE IV.

Tungsten X-Ray Spectrum.

Values of ν/ν_∞ for the K and L Critical Absorption and Emission Lines.

Critical.....	Kα	Lα_1	Lα_2	Lα_3	
Absorption . .	5118. ± 2	750.88 ± .07	849.6 ± .4	890. ± 3.	
K Series[1]....	Kα_2	Kα_1	Kβ	Kγ	
Emission....	4270.6 ± .6	4368.3 ± .6	4947.2 ± .8	5091. ± 2	
L Series.....	Ll	Lα_2	Lα_1	Lη	
Emission....	543.9 ± 3	614.10 ± .12	618.62 ± .05	642.9 ± .3	
L Series.....	Lβ_4	Lβ_1	Lβ_3	Lβ_2	Lβ_5
Emission....	701.8 ± .2	712.53 ± .05	723.17 ± .18	733.75 ± .07	756.9 ± .4
L Series.....	Lγ_1	Lγ_2	Lγ_3	Lγ_4	
Emission....	831.39 ± .06	855.3 ± .3	860.0 ± .3	888.1 ± .5	

In the PHYSICAL REVIEW for July, 1919, Duane and Shimizu published an account of experiments which showed that each of the α emission frequencies in the K series equaled the difference between the K critical absorption frequency and one of the L critical absorption frequencies. Theoretically this should be true provided that all the atoms (of the same chemical element) are exactly alike, *i.e.*, have the same kinds of orbits: for, if W and W_1 represent the amounts of energy in an atom of

[1] The values for the K series emission lines are taken from a paper by Duane and Stenström, presented to the Physical Society in February, 1920. See the PHYSICAL REVIEW, April, 1920, p. 328.

tungsten when in its natural state and when one electron has been removed from the K orbit respectively, the K critical absorption frequency is given by the equation

$$h\mathrm{K}a = W_1 - W. \tag{1}$$

Similarly, if W_2 represents the energy of the system when one of the electrons has been removed from an L orbit, the corresponding L critical absorption frequency is given by the equation

$$h\mathrm{L}a = W_2 - W. \tag{2}$$

According to the theory a Kα characteristic X-ray is emitted when an electron falls from the La orbit to the Ka orbit, and during this transfer the energy of the atom changes from W_2 to W_1. The difference between these amounts of energy is radiated at a frequency Kα given by the equation

$$h\mathrm{K}\alpha = W_1 - W_2. \tag{3}$$

From equations (1), (2) and (3)

$$\mathrm{K}\alpha = \mathrm{K}a - \mathrm{L}a. \tag{4}$$

And this is the relation found by experiment to hold within the limits of error.

If, however, some atoms contain circular orbits and others elliptic orbits, both Ka and La will have different values for the different kinds of atoms. In fact all critical absorption, critical ionization and emission lines will have complex structures. We have not been able to observe such a structure in the absorption drops for chemical elements of high atomic weight. Further the data obtained this year corroborate the results arrived at last year to within the limits of experimental errors. These errors are smaller than those of last year's measurements, for (*a*) the wave-lengths are averages of a larger number of individual determinations, (*b*) some of them were measured in spectra of higher orders and (*c*) the thin glass window in the X-ray tube allowed a larger amount of X-ray energy to emerge from the tube.

The following values taken from Table III. show the precision with which the Kα emission frequencies equal the differences between the critical absorption frequencies.

TABLE V.

Tungsten X-Ray Spectra. Values of ν/ν_∞.

Critical Absorption	Emission Lines
$\mathrm{K}a - \mathrm{L}a_1 = 4366.9 \pm 2.1$	$\mathrm{K}\alpha_1 = 4368.3 \pm .6$
$\mathrm{K}a - \mathrm{L}a_2 = 4268.2 \pm 2.4$	$\mathrm{K}\alpha_2 = 4270.6 \pm .6$

It is impossible to test directly the above law as applied to the L and the M series, for the M critical absorption wave-lengths have not been measured for tungsten.

Theoretically,[1] however, if two emission lines in the L series are produced by electrons falling from the *same* outer orbit to the La_1 and La_2 orbits respectively, the difference between their frequencies should equal that between the two critical absorption frequencies (except for the possible small correction due to the complex structure of the lines as explained above). The difference between the two critical absorption frequencies is

$$La_2 - La_1 = 98.7 \pm .5.$$

Turning to the emission lines we find that the following three pairs have frequency differences that equal the difference between the two critical absorption frequencies to within the limits of experimental error:

$$L\eta - Ll = 99.0 \pm .6, \qquad L\beta_1 - L\alpha_2 = 98.4 \pm .2,$$

$$L\gamma_2 - L\beta_5 = 98.4 \pm .7.$$

This would seem to indicate that the electrons producing the two lines in a pair fall from the same outer orbit. For instance we may suppose that $L\alpha_2$ and $L\beta_1$ are due to electrons falling from one of the M orbits. Measurements of the absorption frequencies for thorium and uranium which the authors presented to the Physical Society in April agree very well with this hypothesis. Further we may assume that Ll and $L\eta$ are produced by electrons falling from an orbit between the L and the M orbits. This orbit, however, has not been identified by means of a critical absorption frequency in the case of any chemical element. On the other hand there appears to be some difficulty in the theoretical interpretation in the case of the third pair, for the frequencies of the emission lines $L\beta_5$ and $L\gamma_2$, are greater than those of the critical absorption frequencies La_1 and La_2 respectively.

The difference between the frequencies of a fourth pair of emission lines is almost, but not quite equal to that between the critical absorption frequencies, namely

$$L\gamma_1 - L\beta_2 = 97.5 \pm .1.$$

It would seem that in this case the electrons producing the lines did not come from exactly the same outer orbit.

Siegbahn[2] finds that the difference in frequency between the lines in these pairs decreases slightly as the frequency itself increases.

[1] Compare an interesting discussion of this subject by A. Sommerfeld in Atombau und Spektrallinien, Chapter 3.

[2] Phil. Mag., Nov., 1919.

Sommerfeld (Atombau und Spektrallinien, Chapter 5) has deduced a formula for this L series frequency difference from his theory of elliptic orbits. Making the relativity correction for the change of mass of an electron with its velocity he finds that the energy of an electron travelling in an elliptic orbit differs somewhat from that of the electron in the corresponding circular orbit. This means that those atoms which have elliptic L orbits produce spectra that differ in frequency from the spectra of atoms with circular L orbits. Sommerfeld's equation for this difference $\Delta\nu$ in frequency (divided by ν_∞) reduces to

$$\frac{\Delta\nu}{\nu_\infty} = \frac{1}{\alpha^2}\left(\sqrt{2}\sqrt{1+\sqrt{1-b^2}}-\sqrt{4-b^2}\right),$$

for the L series. In this equation

$$\alpha = \frac{2\pi e^2}{hc} = 7.295 \times 10^{-3}, \qquad \text{and} \qquad b = \alpha(N-n),$$

where e = the electron's charge, h = Planck's constant and c = the velocity of light.

The function representing the frequency difference, varies roughly as the fourth power of the atomic number, N, of the chemical element. It contains an arbitrary constant, n, the value of which he deduces from the wave-lengths in the X-ray spectra of a great many chemical elements. This value is $n = 3.63$. Putting it and $N = 74$ (for tungsten) in the formula we get 97.9 for the value of $\Delta\nu/\nu_\infty$, which agrees very well with our experimental results.

Sommerfeld recognizes the difficulty of giving a satisfactory physical interpretation to the above value of n (l. c.). Further it is worth noting that the formula does not take into account the changes in the energy of the other electrons in the atom when one of them is removed. These energy changes for the other electrons in the L orbit itself do not appear to be negligible, although, of course only the differences between their values for elliptic and circular orbits would enter into the equation.

HARVARD UNIVERSITY.

ON THE EFFECTIVE CAPACITY AND RESISTANCE OF A CONDENSER FOR HIGH FREQUENCY CURRENTS.[1]

BY F. C. BLAKE.

SYNOPSIS.

Capacity Independent of Frequency.—By careful experiments on the free oscillations of a Lecher system as the capacity of the end condensers is changed by increasing the elastic coupling it is found that the capacity of an air condenser is independent of the frequency of oscillation.

Rayleigh's Equation for the effective stiffness (elastance) of a circuit due to the mutual elastic reactions between two circuits each containing inductance, capacity and resistance is verified. Use is made of his equation for effective resistance to determine the mutual resistance of two reacting circuits.

IN a previous paper Blake and Jackson[2] reported their investigation of the relative intensities of the free vibrations of a Lecher system as the side-on distance y, Fig. 1, was varied and the writer[3] has developed a theory to explain the experiments. The present paper reports on the

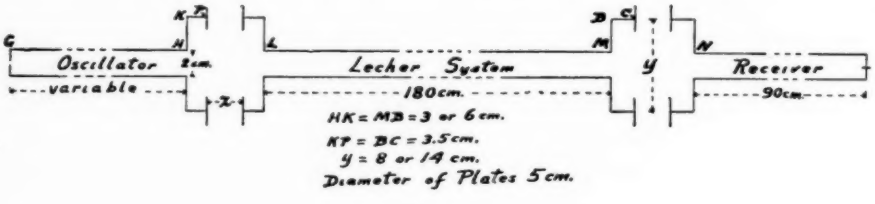

Fig. 1.

results obtained as the face-on distance x between the plates was varied. The experimental results are compared with Lord Rayleigh's theory for the behavior of a vibration system having kinetic and potential energy and dissipation.

The apparatus used has been described in previous papers. All the experimental variations made are shown in Table I. Two different values of y were used, 8 and 14 cm. The distance x was varied from 11 cm. down to 0.684 cm., the shortest distance it was feasible to use because of mutual interference between the strings holding the plates.

[1] Read before American Physical Society, Nov. 28, 1919.

[2] Ohio Journal of Science, XVIII., p. 145, 1918.

[3] Ohio Journal of Science, XVIII., p. 163, 1918.

TABLE I.

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.
y Cm.	x Cm.	O Cm.	L Cm.	R Cm.	Bridge Position.					Unassigned Peaks.	Mean Observed Wavelength.				Reduced Wavelength, λ_s.					End Correction Cm.	l_s.	$\frac{K_0}{K}$.	Mean $\frac{K_0}{K}$.	$\frac{K_0}{E.S.U.}$	k.	c_{12}.	b_{12} Ohms.	R' Ohms.
					$s=1$.	3.	5.	7.	9.		$s=3$.	5.	7.	9.	$s=1$.	3.	5.	7.	9.									
8	11	95.0	180.1	90.0	149.8	77.2 222.5	64.0 106.8 192.9 236.2														97.0 24.35 11.0 6.1 3.8	13.18 13.17 13.19 13.16 13.18	13.18	0.832				
8	11	90.3	180.1	90.0	150.0	77.2 222.5	64.0 106.8 192.8 235.8	89.3 119.7 180.0 210.2			145.3	86.0	60.6	46.6	440.1	145.3	86.0	60.6	46.6	+0.5								
8	5	99.0	180.1	90.0	150.0 broad	76.5 224.0	64.0 107.2 193.6 237.0			221.2	147.5	86.4	147.5															
8	5	95.0	180.1	90.0	150.0 broad	76.4 224.0	64.6(?) 106.7 193.3 236.9			62.4 220.2 222.5	147.6	86.6																
8	5	90.3	180.1	90.0	149.0 150.0	76.3 224.0	63.4 106.5 193.5 237.0	88.8 119.1 — 210.5	126.3 173.4	191.2 209.0 234.5	147.7	86.9	60.8	47.1	450.7	147.8	86.9	60.8	47.1	+0.1	96.6 22.7 9.7	16.29 16.38	16.34	1.031				
8	2	99.0	180.1	90.0	144.7 154.7	72.3 149.6 227.0	— 99.7 191.2 237.5			64.0 66.3 106.2 110.2	154.7	91.5																
8	2	90.3	180.1	90.0	144.3 154.9	75.2 151.3 228.2	61.8 106.4 195.0 239.3	88.6 119.4 181.2 212.0	125.6 174.0	71.0 197.0 205.9 214.5	153.0	88.7	61.75	48.4	481.0	154.3	89.0	61.9	48.2	−0.1	96.4 19.2 7.4	24.67 24.73 24.60	24.67	1.556				
8	0.684	113.8	180.1	90.0	131.5 161.8	61.7 145.5 broad 231.3				90.5 103.7 109.9 151.8 155.7 175.9 186.4 200.5 208.8 215.3	169.6																	

					133.0	68.7	99.9				92.8																					
8	0.684	99.8	180.1	90.0	162.5	151.2	147.0				118.8	209.6	165.7	93.8																		
						234.4	193.7				121.8	219.0																					
								88.2																								
						71.9	105.7	119.4															96.3	51.04								
					133.6	153.8	151.5		78.9	93.8	204.5												12.8	50.90								
8	0.684	90.1	180.1	90.0	163.0	235.9	197.3	182.0					164.0	91.6	62.5	47.8(?)	571.2	167.0	92.2	62.7	−0.2	4.1	51.17	51.04	3.221							
								213.3	222.5	123.0	209.7																					
						76.5	105.7																101.50	9.18		0.580						
14	11.0	94.2	180.0	90.0	150.0								147.0	88.6			442.6	147.0	88.6		+2.00	28.00	9.18						1,966		
						223.5	194.3																12.90	10.85		0.685						
						76.3	105.5																101.22	9.95		0.628						
14	9.0	94.2	180.0	90.0	150.0								147.5	89.0			444.4	147.5	89.0		+1.72	27.47	9.95						1,868		
						223.8	194.5																12.22	12.13		0.765						
						76.1	105.5																101.00	11.09		0.700						
14	7.5	94.2	180.0	90.0	150.0 broad								148.3	89.2			448.0	148.5	89.2		+1.50	26.75	11.10						1,738		
						224.4	194.7																12.20	12.96		0.817						
						75.9	105.4																100.77	12.19		0.770						
14	6.0	94.2	180.0	90.0	148.8 150.5								149.1	89.5			451.4	149.4	89.5		+1.27	26.07	12.21			0.0151	0.0092	1,628	− 79		
						225.0	194.9																11.27	14.08		0.817						
						75.7	105.3																100.55	14.43		0.910						
14	4.5	94.2	180.0	90.0	147.6 151.5	150.5						218	150.6	89.8			459.2	151.4	89.9		+1.05	24.85	14.43			0.0324	0.0198	1,446	−158		
						226.3	195.1																10.65	15.53		0.980						
						75.2	104.8																100.40	16.62		1.048						
14	3.5	94.2	180.0	90.0	146.5 153.0	151.2						216.5	152.3	90.6			467.0	153.3	90.6		+0.90	23.75	16.60			0.0556	0.0340	1,304	−242		
						227.5	195.4																9.80	17.84		1.126						
						74.4	104.6																100.26			1.267						
14	2.5	94.2	180.0	90.0	144.7 154.7	151.2						213.8	154.8	91.5			479.6	156.2	91.6		+0.76	22.16	20.08			0.0822	0.0502	1,110	−304		
						229.2	196.1					221.8											8.66	21.58		1.362						
						72.5	103.6																100.12	28.17		1.777						
14	1.5	94.2	180.0	90.0	140.0 156.6	151.6							160.1	93.1			508.9	162.0	93.2		+0.62	19.12	28.16			0.1310	0.0801	787	−344		
						232.6	196.7					207.2											6.92	29.48		1.860						
						70.2	102.8																100.05	37.23		2.349						
14	1.0	94.2	180.0	90.0	136.0 159.8	151.8						208.7	165.0	94.4			540.7	167.0	94.4		+0.55	16.50	37.23			0.1766	0.1079	503	−295		
						235.2	197.2	214.3		83.7	220.4												5.65	38.04		2.401						
						68.1	102.2	83.2															100.02	50.91								
					130.5	153.1	150.0	116.3				178.1											13.62	50.92								
14	0.684	94.2	180.0	90.0	163.6	238.5	238.5	181.8		122.0			170.4	95.6	65.7		586.5	172.8	95.6	65.3	+0.52	4.42	50.90	50.91	3.212	0.2243	0.1371	65	− 45		
								215.1				219.6											2.07	51.48								

EXPERIMENTAL RESULTS.

Figure 2 shows the results for $y = 14$ cm., the oscillator being kept constant at 94.2 cm., straight away length *GH* (Fig. 1).

As was to be expected all wave-lengths are increased as the coupling becomes closer and for couplings closer than 6 cm. the fundamental

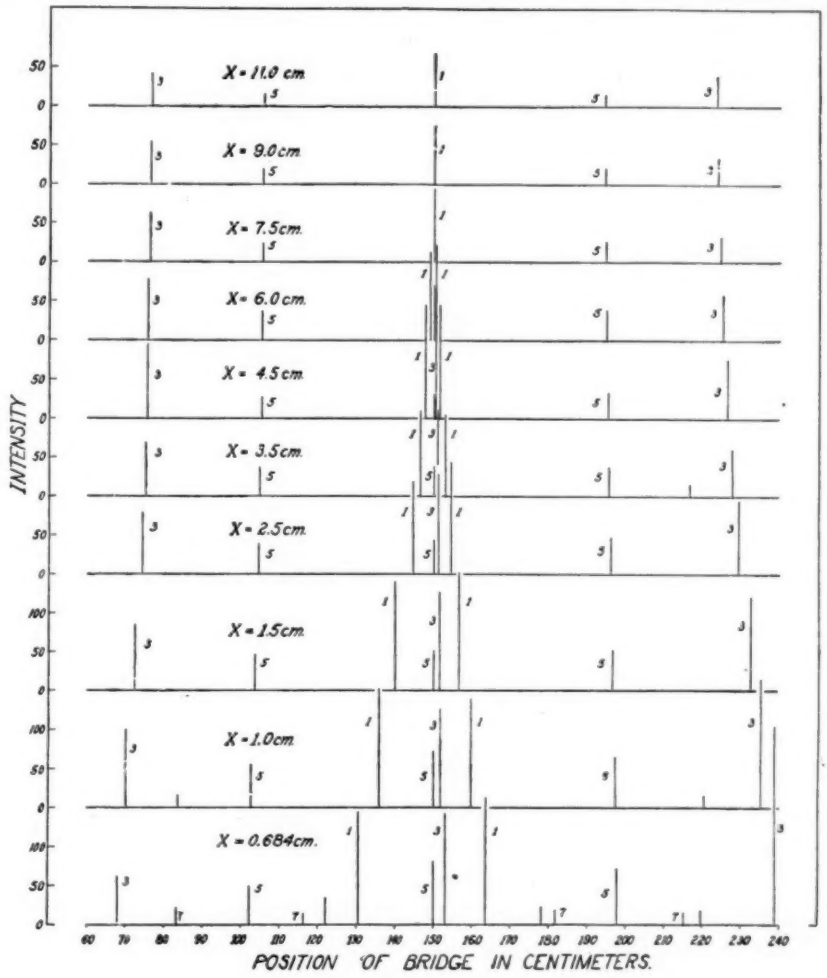

Fig. 2.

has split up into two tones whose difference in period becomes greater the tighter the coupling. It is manifest moreover that the position of any one tone is dependent upon the oscillator length and that as the coupling is made tighter the length of oscillator necessary to hold a given tone in the exact middle of the Lecher wires also varies. This is shown

more clearly in Fig. 3 ($y = 8; x = 0.684$) three different oscillator lengths being employed. In the top curve of Fig. 3 is shown the actual slopes of all the peaks observed. It is manifest in many of the curves of Figs. 2 and 3, especially for the closer couplings, that there are some peaks that are not true harmonics of the Lecher systems but may be thought of either (*a*) as a mixture of two neighboring harmonics when the oscillator length is too short to be the optimum length for one set of harmonics and two long for the next set; or (*b*) as one of the possible frequencies of the entire system vibrating as a whole. That the system of peaks

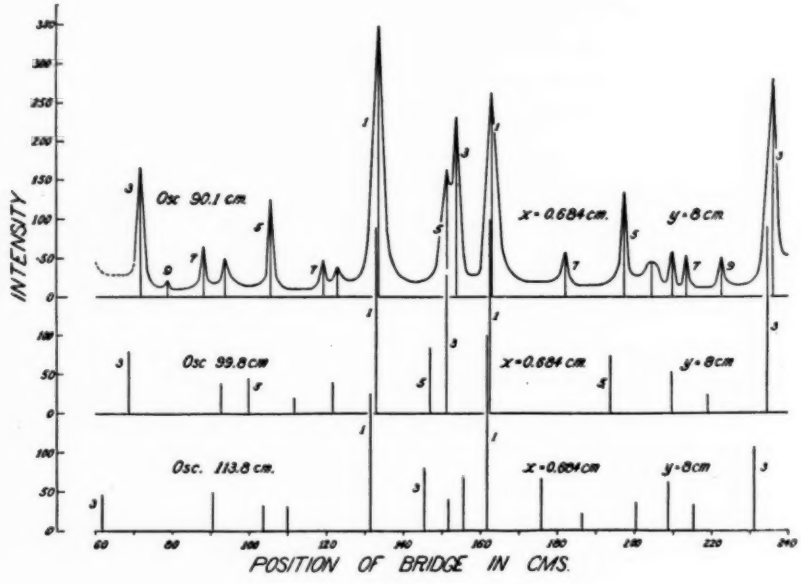

Fig. 3.

becomes complicated for the closer couplings by the introduction of these extraneous peaks can be clearly seen from an inspection of Table I. Column 10 marked "Unassigned Peaks" has quite a few peaks to its credit.

Blake and Sheard[1] and Blake and Jackson[2] have shown that for very loose couplings a change in the oscillator length practically has no effect on the position of a given tone. For the closer couplings of the present paper, on the other hand, the case is far different. The position of a given tone is more strongly affected by the oscillator length the tighter the coupling. The same thing is true for a variation in the length of the spark gap. The true position of a given peak can therefore be found

[1] PHYS. REV., N. S., IX., p. 177, 1917.

[2] L. c.

only by locating it for a given oscillator length which is known to be at or near the optimum spark gap length for that tone. To eliminate errors that would otherwise exist both spark gap curves and bridge curves were taken for the curves shown in this paper, after the manner adopted by Blake and Jackson (q.v.). For the closest coupling (0.684 cm.) the error in position due to ignoring the proper length of spark gap could be as much as 2 cm. for some tones. Even with the precautions

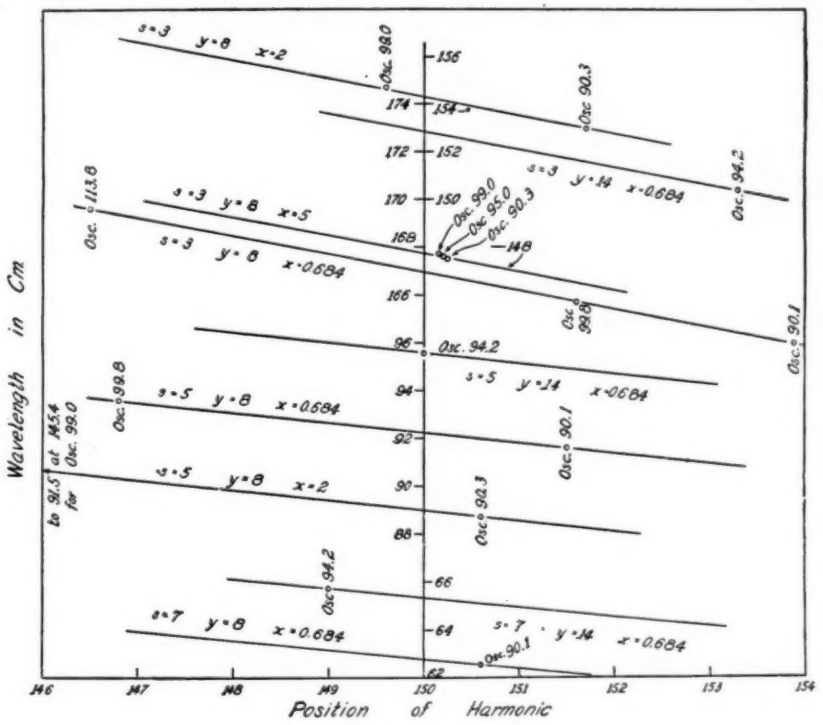

Fig. 4.

here taken there seemed to be an occasional displacement of a peak. For instance, in the lowest curve of Fig. 3 the third harmonic persistently read too low, viz., 145.5 cm. instead of 146.4 cm. However, the peak was very broad like that shown in the uppermost curve at 204.5 cm., showing that two peaks were close enough together to join and become one.

The influence of oscillator length upon the position of a given peak is shown very clearly in Fig. 4 for the third, fifth and seventh harmonics. In order properly to interpret the experimental results it becomes necessary to know what length of oscillator would bring the middle peak for any given tone exactly at the center of the Lecher system. Plotting the

displacements shown in Fig. 3 against the wave-lengths we get those curves of Fig. 4 marked "$y = 8$; $x = 0.684$." The same thing was done for the other values of x shown in Table I., for $y = 8$ cm.

Consider for instance the curve marked $s = 3$; $y = 8$; $x = 0.684$. For the three different oscillator lengths all three points lie on a straight line whose slope is 0.76. Indeed the other curves show that the slope is independent of x. For the fifth harmonic the slope is seen to be 0.42, and again independent of x. For the seventh harmonic only one point on the curve was available, but the slope cannot be far different from that taken, viz., 0.33. The curve marked $s = 3$; $y = 8$; $x = 5$ shows clearly how, for this fairly loose coupling, a variation in oscillator length has but little effect on the position of a given tone, as evidenced by the close proximity of the observed points.

It is clear from Fig. 4 that in order to compare the various tones we must not use the observed wave-length but rather the "reduced" wave-lengths, that is, those that always bring the middle peak for any one set of tones exactly at the center of the Lecher system. In order to determine the reduced wave-lengths in the manner indicated it was necessary that the distance x between the plates should always be changed simultaneously for the two sets of plates at each end of the Lecher system. This condition was always fulfilled experimentally.

The only difference between the results for $y = 8$ cm. and $y = 14$ cm. should be differences due to the increased length of each circuit owing to the wire HK (Fig. 1) being longer for the latter value of y. Each circuit is thereby about 3 per cent. longer. This fact can have but a secondary influence upon the slopes of Fig. 4 for $y = 14$ cm. Only one length of oscillator was used for this value of y, hence the slope for each was taken the same for $y = 14$ cm. as for $y = 8$ cm.

Having thus found for both values of y the reduced wave-lengths which ought to fulfill the Kirchhoff-Abraham[1] equation

$$\frac{2\pi l}{\lambda} \tan \frac{2\pi l}{\lambda} = \frac{Kl}{K_0}, \qquad (1)$$

it is apparent that certain corrections must be made before the experimental results can be properly interpreted. In this equation l is the distance from the bridge position nearest the receiver up to the plate, *measured as if the wire were without a bend*, K_0 the end capacity and K the capacity per unit length of the Lecher system. For instance using the reduced values of λ_s for $s = 3$, 5 and 7 for $y = 8$ and $x = 0.684$, viz., 167.0, 92.2 and 62.7 cm., the value of K_0 calculates 49.95, 48.63

[1] Kirchhoff, Ges. Abh. p. 180; Abraham Föppl, Th. der El., p. 354.

and 39.83 cm. By taking an end correction of 0.2 cm. these results are changed to 50.90, 51.17 and 43.50 respectively, more nearly constant. As only one point on the curve was available for the seventh harmonic the exact slope of the curve was unknown. Moreover, Blake and Jackson have pointed out that a change of one per cent. in the wave length λ_s affects the value of K_0/K 22 per cent. for the seventh harmonic whereas the same change affects the third and fifth only 11 and 15 per cent. respectively.

If one uses the values of the end correction shown in Column 20 of Table I. he gets fairly constant values for K_0/K as shown in column 22. Plotting the values of column 20 we get the lower curve of Fig. 5, a straight line. In column 22 the brace encloses the value of K_0/K for the third and fifth harmonics as being the figures used to determine the

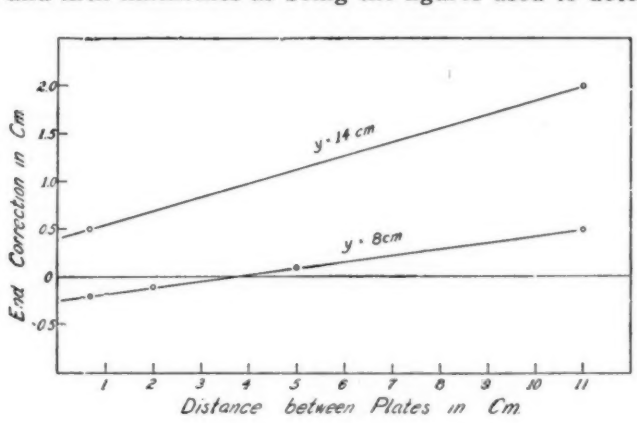

Fig. 5.

mean K_0/K given in column 23. These figures are naturally more accurate than those for the higher harmonics. Of course the figures for the fundamental wave-length in column 15 are found by trial from equation (1) using the value of l for the fundamental (after the end correction has been made) and the value of K_0/K given in column 23.

If we plot the wave-lengths in columns 15 and 16 against the distance x between the plates we get the lower curve of Fig. 6 for the fundamental and third harmonics respectively.

It will be noted that an end correction of 0.5 cm. brought all the results in column 22 for $x = 11$ and $y = 8$ cm. into harmony even up to the ninth harmonic. The mean value for K_0/K is thus found to be 13.18 cm. whereas Blake and Jackson without employing an end correction found 13.70 cm. This small change in their result can in no way materially affect their final results or the theory developed by the author to

explain their results. In this theory, however, there is one thing that needs correction. On page 165 of the reference given the disturbing force is taken as distributed over $2\gamma\lambda/2\pi$. This should be $\gamma\lambda/2\pi$, the method of measurement being such that *all* of this disturbance shows itself in the receiver. Here again, this correction leaves the final equation for the energy measured by the receiver entirely unchanged.

With the lower curve of Fig. 5 as an empirical curve an attempt was made to calculate the end correction for the larger value of y, viz., 14 cm. For this value of y it was found empirically that an end correction of

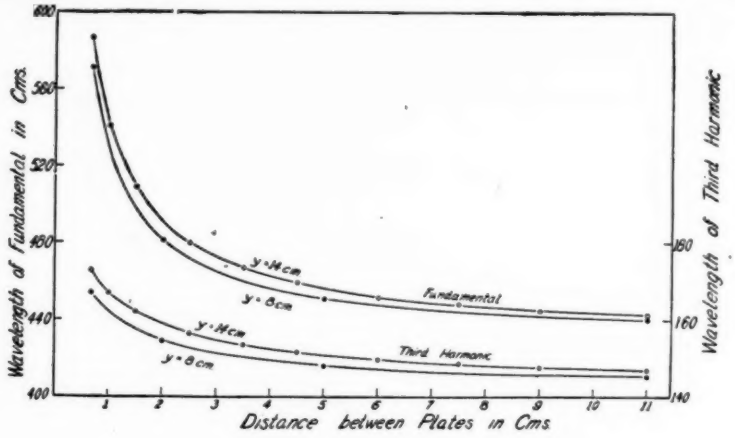

Fig. 6.

0.52 cm. brought K_0/K constant for the smallest value of x, as the table shows.

We proceed to calculate the self-inductance and capacity per unit length of the Lecher system in all its parts. Consider first the straight-away length LM, Fig. 1. The inductance L and the capacity K per unit length are given by the formula

$$L = 4 \log_e \frac{2d}{b} = \frac{1}{v_0^2 K}, \qquad (2)$$

where $2d$ (= 2 cm.) is the distance between the parallel wires and b is the radius of the wires, viz., 0.038 cm., v_0 being the velocity of light. This gives L 15.853 e.m.u. and K = 0.06307 e.s.u. To get L for the length HK we calculate L from (2) for $2d$ = 8 cm. or 14 cm. and then take the mean between this value and the value of L for 2 cm. This gives L 18.620 e.m.u. for y = 8 cm. and 19.745 e.m.u. for y = 14 cm. Now the portion KP of each circuit was a brass rod 3.5 long and 4 mm. diameter. The use of (2), taking b = 0.2, gives L 14.756 e.m.u. for y = 8

and 16.994 for $y = 14$ cm. If we take K for MB to be 0.063 and for BC to be 0.067 we get the following set of figures: $3 \times 18.620 \times 0.063 + 3.5 \times 14.756 \times 0.067 = 7.0$ cm. Subtracting $3.0 + 3.5$ from 7.0 gives 0.5 cm. end correction, the amount empirically found for $y = 8$ and $x = 11$ cm. If we now use the same value of K for $y = 14$ cm. as for $y = 8$ cm. we arrive at the following results $19.745 \times .063 \times 6 + 16.994 \times .067 \times 3.5 = 11.5$ cm. Subtracting $6.0 + 3.5$ from 11.5 gives 2.0 cm., the amount of the end correction for $y = 14$ and $x = 11$ cm. This is an upper limit of the end correction for it is hardly likely that the value of K would be as great when MB (Fig. 1) is 6 cm. as for 3 cm. However, this is in part offset by the presence of the table top some 57 cm. below the Lecher wires which would tend to hold the capacity per unit length up according to the formula

$$K = \frac{1}{2 \cosh^{-1} \frac{h}{b}}, \tag{3}$$

where h is the distance from the ground (57 cm.) b being the radius of the wire. This gives $K = 0.0625$, not far from 0.063.

The empirical value of the end correction found for $y = 14$ cm. and $x = 0.684$ is 0.52 cm. If we accordingly connect the values for $x = 0.684$ cm. and $x = 11$ cm. by a straight line we get the upper curve of Fig. 5 and by graphic interpolation the figures in Column 20 of Table I. are found. This enables us to calculate the value of K_0/K (column 22). It is seen that K_0/K for the thirds and fifths begin to diverge from each other for values of x greater than 1 cm. differing by 15 per cent. for $x = 11$ cm. Since there are two factors involved in arriving at these results neither one of which is known with certainty, this is not particularly surprising; for $y = 14$ cm., neither the slopes of the curves of Fig. 4 nor the amount of the end correction are positively known. For that reason the mean K_0/K is not given in column 23 except for the smallest value of x. Plotting the values of λ for the fundamental we get the upper curve of Fig. 6, the curve for the third harmonic being also shown in the figure.

If we plot the values of the end capacity reduced to electrostatic units (column 24) against the distance x for both values of y we get curves I. and II. of Fig. 7, the curve for $y = 14$ being that obtained from the third harmonic. As can be seen from the table the curve for the fifth harmonic would lie between the one drawn and the one for $y = 8$ cm. The crosses are the values of the condenser capacity calculated from Kirchhoff's

[1] Gessammelte Abhandlungen, p. 112.

equation

$$C = \frac{r^2}{4x}\left\{1 + \frac{x}{\pi r}\left[\log_e \frac{16\pi(x+t)r}{x^2} + \frac{t}{x}\log_e \frac{x+t}{t} - 1\right]\right\}, \qquad (4)$$

in which r, the radius of each plate, was 2.5 cm. and t, its thickness, was 1 mm., while x the distance between the plates was made to vary. Of course the true capacity of a condenser can be obtained (presumably for direct current) only for values of x and t small compared to r, as has

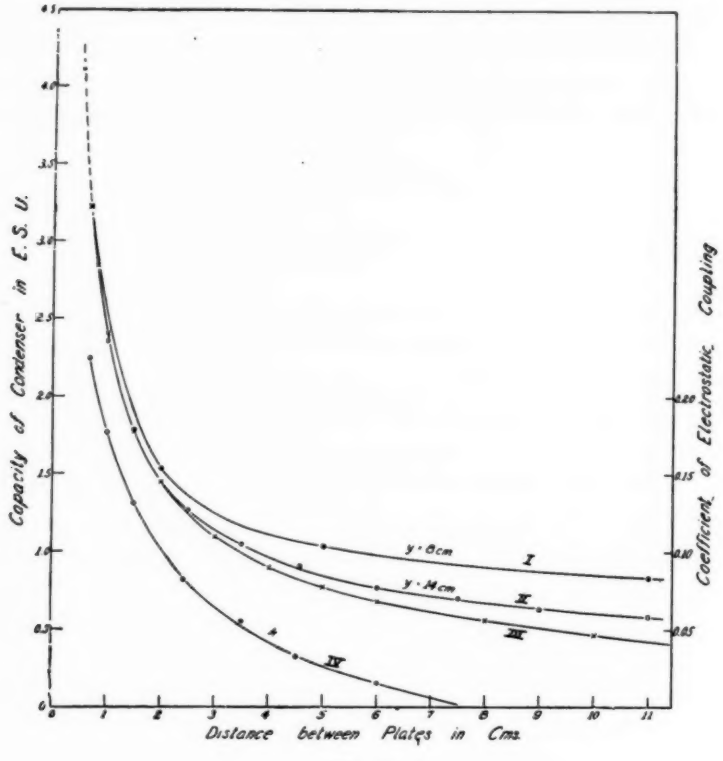

Fig. 7.

been stated above. An inspection of the upper curves of Fig. 7 shows at once that for both values of y theory and experiment agree for small values of x, Table I. giving the capacity for $x = 0.684$ as 3.212 e.s.u. for $y = 14$ cm.; the value being only slightly larger, viz., 3.221 for $y = 8$ cm. due to the close proximity of the other set of plates. Equation (4) gives the value 3.212 e.s.u. The writer interprets this agreement between theory and experiment to lead at once to two important results. First, *the capacity of an air condenser is entirely independent of frequency*. Secondly, when x is as small as 0.684 cm. and y as big as

14 cm. we may practically say that no lines of force run from one plate to another of the same circuit.

It would be interesting to know the exact shape of the curve (Fig. 7) connecting capacity with distance between the plates on the assumption that no lines of force run between plates of the same circuit even for the largest values of x used. An empirical equation for the curve could then be found and the mathematical physicists could try their hand at the problem for circular plates just as many writers have done so admirably for spherical balls.[1] If one looks up the derivation of Kirchhoff's formula (Eq. 4) one finds that on account of analytical difficulties various approximations have been made. Since in the derivation x and t are taken small compared to r equation (4) could not be expected to hold for x greater than 1 cm. say. For this value of x the experimental result practically agrees with equation (4). On account of the limitation imposed with respect to x and r it is not altogether justifiable to keep second order terms but if a second approximation[2] is made equation (4) becomes

$$C = \frac{r^2}{4x}\left\{1 + \frac{x}{\pi r}\left[\log_e \frac{16\pi(x+t)\left(r+\frac{x}{4}\right)}{x^2} + \frac{t}{x}\log_e \frac{x+t}{t} - 1\right]\right\}. \quad (5)$$

In Fig. 7, curve III. is plotted from Kirchhoff's formula (Eq. 4) and the extra term in (5) has no appreciable effect for values of x less than 3 cm. For $x > 3$ cm. (5) gives a value of C continually increasing compared to (4) being for $x = 10$ cm. about 25 per cent. greater than (4) gives and almost exactly the value obtained experimentally by Curve II. This is mentioned merely to show that (4) gives too small a value of C for the larger values of x and that accordingly the true value of the capacity of a parallel plate condenser when the distance between the plates ceases to be small compared to their radius probably lies roughly half way between Curves II. and III. of Fig. 7.

Further Comparison with Theory.

It is desirable to compare the results of this paper with the theoretical results given by Lord Rayleigh[3] for the mutual reaction between two circuits each having kinetic and potential energy and dissipation, *i.e.*, inductance, capacity and resistance. Lord Rayleigh obtains for the effective "stiffness" S' and the effective resistance R' the following equations:

[1] See for instance Russell's Alternating Currents, Second Edition, Chap. VIII.

[2] Cordial acknowledgment is here made to my friend, Professor R. D. Bohannan, for deriving this second order term.

[3] Phil. Mag., XXI., pp. 369-381; Scientific Papers, Vol. II., p. 484.

$$S' = c_{11} - p^2a_{11} - \frac{(c_{12} - p^2a_{12})^2}{c_{22} - p^2a_{22}} + \frac{p^2[b_{12}(c_{22} - p^2a_{22}) - b_{22}(c_{12} - p^2a_{12})]^2}{(c_{22} - p^2a_{22})[(c_{22} - p^2a_{22})^2 + p^2b_{22}^2]}, \quad (5)$$

$$R' = b_{11} - \frac{b_{12}^2}{b_{22}} + \frac{[b_{12}(c_{22} - p^2a_{22}) - b_{22}(c_{12} - p^2a_{12})]^2}{b_{22}[(c_{22} - p^2a_{22})^2 + p^2b_{22}^2]}. \quad (6)$$

In these equations a_{11}, a_{22}; b_{11}, b_{22}; c_{11}, c_{22} are the coefficients of self inductance, self resistance and self elastance, a_{12}, b_{12}, c_{12} being the corresponding mutual coefficients. Moreover it is to be remembered that the self coefficients are to be determined for each circuit when it alone is in the field. Thus, for instance, c_{22} is the self elastance of the secondary circuit, that is, it is the reciprocal of the capacity of the condenser plate attached to the secondary circuit, this capacity being measured when the secondary circuit is infinitely removed from the primary circuit. Theoretical writers have frequently taken $c_{22} - p^2a_{22}$ and $c_{11} - p^2a_{11}$ each equal to zero provided p is the natural frequency of each circuit when far removed from the other. In practice, however, this is not justifiable because of the impossibility of neglecting the distributed capacity of the discharge wires. Hence equation (1) rather than Kelvin's formula for condenser discharge applies. Accordingly in the expression $c_{11} - p^2a_{11}$ and $c_{22} - p^2a_{22}$ of (5) and (6) we must substitute for p the natural frequency n that fulfills equation (1). Rayleigh's equations thus become

$$S' = c_{11} - n^2a_{11} - \frac{(c_{12} - p^2a_{12})^2}{c_{22} - n^2a_{22}} + \frac{p^2[b_{12}(c_{22} - n^2a_{22}) - b_{22}(c_{12} - p^2a_{12})]^2}{(c_{22} - n^2a_{22})[(c_{22} - n^2a_{22})^2 + p^2b_{22}^2]}, \quad (7)$$

$$R' = b_{11} - \frac{b_{12}^2}{b_{22}} + \frac{[b_{12}(c_{22} - n^2a_{22}) - b_{22}(c_{12} - p^2a_{12})]^2}{b_{22}[(c_{22} - n^2a_{22})^2 + p^2b_{22}^2]}. \quad (8)$$

We proceed to calculate the quantities in these equations that are known from geometrical considerations for the case $y = 14$ cm., $x = 0.684$ cm.

Of the resistance terms b_{12} will be spoken of below; b_{11} can be calculated from the formula[1]

$$\frac{R}{R_0} = \frac{\pi h}{(h^2 - d^2)^{\frac{1}{2}}}\sqrt{\frac{nd^2}{\rho}} + \frac{1}{8} - \frac{[h - (h^2 - d^2)^{\frac{1}{2}}][d^2 + h(h^2 - d^2)^{\frac{1}{2}}]}{2(h^2 - d^2)^{\frac{3}{2}}}, \quad (9)$$

where R is the high and R_0 the low frequency resistance. For the case here considered $h = 2$ cm. and $d = 0.076$ cm. so (9) reduces to

$$\frac{R}{R_0} = \pi\sqrt{\frac{nd^2}{\rho}} + \frac{1}{8}. \quad (10)$$

Taking ρ, the resistivity of copper, to be 1,755 and $\lambda = 500.4$ cm. $= v_0/n$

[1] Cohen, Calculation A. C. Problems, page 8, formula 12.

we get $R/R_0 = 44.25$. Now R_0, the resistance of 200 cm. of copper wire of 0.076 cm. diam. is .0775 ohms and hence $R = b_{11} = 3.43$ ohms. To get b_{22} we must add to b_{11} the resistance of the detecting thermal couple, 4.16 ohms. The couple was made of iron and constanan wire of diameter 0.02 mm., hence its resistance was independent of the frequency of oscillation.

To get c_{11} we must first know the capacity of a circular brass plate 5 cm. in diameter and 1 mm. thick when alone in space. The capacity of such a plate of infinitesimal thickness is known to be $2r/\pi$ e.s.u. So far as the writer knows no one has yet worked out the necessary correction for a plate of finite thickness. It is believed, however, that no appreciable error has been made in correcting for the thickness in the following way. The value of the capacity of a circular plate condenser has been calculated from equation (4) both for $t = 0$ and for $t = 1$ mm. In this way Fig. 8 is obtained, in which the ordinate represents the

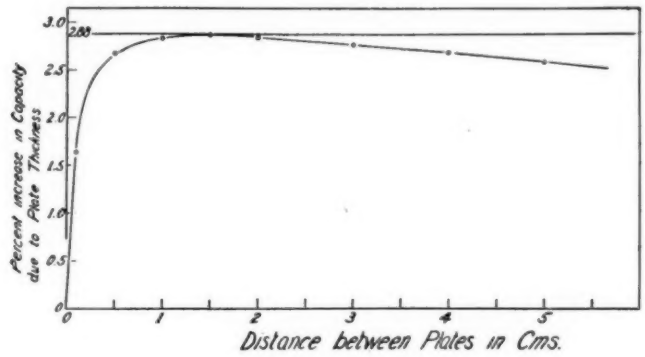

Fig. 8.

per cent. increase in capacity due to the finite thickness, the abscissa being the distance between the plates. It is argued that the fact that the curve after rising to a maximum decreases again (*but very slowly*) is due to the fact that the formula is not admissible for distances between the plates that are not small compared to their diameter. Hence the asymptote for infinite distance will be *only very slightly* above the maximum point; it is taken as 2.88 per cent. Whence $1/c_{11} = 1.0288 \times (2r/\pi) = 1.637$ e.s.u., giving $c_{11} = c_{22} = 0.6109$ e.s.u.

We can get c_{12} by noting how the fundamental tone splits in two when the coefficient of coupling becomes appreciable. We have for k, the coefficient of coupling, $k = (\lambda_2^2 - \lambda_1^2)/(\lambda_2^2 + \lambda_1^2)$ where λ_1 and λ_2 are the two observed wave-lengths for the fundamental tone. From this equation k is plotted as Curve IV., Fig. 7. If δ is the difference

between the two figures given in column 5 of Table I., we have $\lambda_2 - \lambda_1 = 4\delta$ and furthermore $\lambda_2^2 + \lambda_1^2 = 2\lambda^2$ where λ is the fundamental wave-length fulfilling equation (1). Except for the larger values of k no appreciable error is made in taking $\lambda_2 + \lambda_1 = 2\lambda$. Now it will be proved in another paper that $k^2 = c_{12}^2/(c_{11}c_{22})$. If, as here, $c_{11} = c_{22}$ we have $c_{12} = kc_{11} = kc_{22}$ and for $y = 14$, $x = 0.684$ we get $c_{12} = 0.1371$ e.s.u.

We get a_{11} directly from equation (2) by multiplying by $l_1 = 100.02$ cm., giving $a_{11} = a_{22} = 1585.0$ e.m.u. $= 1585/v_0^2$ e.s.u.

To get a_{12} we proceed as follows (see Fig. 9). The mutual inductances

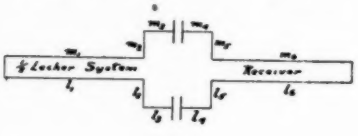

Fig. 9.

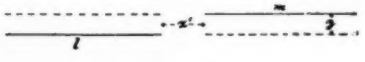

Fig. 9a.

between l_1 and l_6, l_3 and l_4, l_1 and m_6, l_3 and m_4, l_3 and l_6, l_3 and m_6, l_2 and m_5, were each calculated by means of a formula very kindly supplied by Dr. F. W. Grover,[1] formerly of the Bureau of Standards. The writer desires here to express his hearty appreciation of this assistance. The formula is

$$M = \alpha \log_e[\alpha + (\alpha^2 + z^2)^{1/2}] - \beta \log_e[\beta + (\beta^2 + z^2)^{1/2}]$$
$$- \gamma \log_e[\gamma + (\gamma^2 + z^2)^{1/2}] + \delta \log_e[\delta + (\delta^2 + z^2)^{1/2}]$$
$$- [(\alpha^2 + z^2)^{1/2} - (\beta^2 + z^2)^{1/2} - (\gamma^2 + z^2)^{1/2} + (\delta^2 + z^2)^{1/2}], \quad (11)$$

where $\alpha = l + m + x'$, $\beta = l + x'$, $\gamma = m + x'$, $\delta = x'$ (Fig. 9a). To get the mutual inductance between l_2 and l_5 use was made of formula (174) of B.S. Cir. No. 74, viz.,

$$M = 2\left[l \log_e \frac{l + (l^2 + d^2)^{1/2}}{d} - (l^2 + d^2)^{1/2} + d \right], \quad (12)$$

in which for $y = 14$ cm. we have $l = 6$ cm. and $d = 7.89$ cm. In getting the other factors we have $l_1 = l_6 = 90$ cm., $l_3 = l_4 = 3.5$ cm., $x' = 0.89$ cm. for l_3l_4 and 7.89 cm. for l_1l_6, while $z = 2$ cm. for both of these. For l_3l_6, $x' = 4.39$ cm. and $z = 6$ cm.

If for the moment we represent the mutual inductance between l_2 and l_5, say, by l_2l_5 and do the same for the other factors we have

[1] It should be stated that for circuits such as are used in this paper Dr. Grover's formula lends itself to calculation much more easily than the geometric formulas 174 to 182 of Circular No. 74 of the Bureau of Standards. This is due to the fact that the distance between the Lecher wires was small compared to their length.

$$a_{12} = 2[(l_1l_6 - l_1m_6) + (l_3l_4 - l_3m_4) + (l_2l_5 - l_2m_5) + (l_3l_6 - l_3m_6)]$$
$$= 2[(102.64 - 102.48) + (2.71 - 0.83) + (4.37 - 2.84) + (9.99 - 8.68)]$$
$$= 9.76 \text{ e.m.u.} = \frac{9.76}{v_0^2} \text{e.s.u.}$$

This value is of course the low frequency mutual inductance.. On the same basis the low frequency self inductance of the first circuit is 1,597 instead of 1,585 e.m.u. Thus for the closest coupling ($x = 0.684$ cm.) while $c_{12}/c_{11} = 22.4$ per cent., a_{12}/a_{11} equals only 0.6 per cent. Hence for all except the closest coupling we may take $a_{12} = 0$ practically.

If the last term in (7) is neglected we have

$$S' = c_{11} - n^2a_{11} - \frac{(c_{12} - p^2a_{12})^2}{c_{22} - n^2a_{22}}. \tag{13}$$

Substituting the values calculated above for the case $y = 14$ cm., $x = 0.684$ cm. we get

$$S' = 0.6109 - \frac{4\pi^2 \cdot 1585}{500.4^2} - \frac{\left(0.1371 - \frac{4\pi^2 \cdot 9.76}{586.5^2}\right)^2}{0.3610} = 0.3098 \text{ e.s.u.}$$

The reciprocal of the observed capacity is $1/3.212 = 0.3113$ e.s.u. There is thus agreement to within 0.48 per cent. Had a_{12} been neglected the agreement would not be quite so good, viz., 0.71 per cent.

From the nature of the terms in (7) it is clear that $c_{11} - n^2a_{11}$ is independent of x while the fractional terms depend upon x. Of the latter the first term decreases as x increases while the second is intrinsically positive. There can be no question, it seems to the writer, that the curve for $y = 14$ cm. of Fig. 7 is a close approximation to the true relationship between the effective capacity of a circuit and its nearness to a second similar circuit. (See above remarks on Curves II. and III., Fig. 7, however.) Accordingly since as x increases the only quantities that change are a_{12}, c_{12} and b_{12} and since it is obvious that a_{12} and c_{12} decrease as x increases the quantity b_{12} must increase as x increases. If we call the difference between the two sides of (13) d^2 and treat (7) as an equation to determine b_{12} for different values of x we get the upper curve of Fig. 10. The values of b_{12} thus found are shown in column 27 of the table. If these are substituted in (8) we get the value of R' shown in column 28. It will be noted that all the values of R' are negative with an absolute minimum for $x = 1.5$ cm. about.

In getting the value of b_{12} since p^2b_{22} is negligible compared to $c_{22} - n^2a_{22}$ we have

$$b_{12} = \frac{d}{p}(c_{22} - n^2a_{22})^{1/2} + b_{22}\frac{c_{12} - p^2a_{12}}{c_{22} - n^2a_{22}}. \tag{14}$$

The second term is small compared to the first term so this reduces to

$$b_{12} = \frac{d}{p}(c_{22} - n^2 a_{22})^{1/2} = \frac{586.5}{2\pi} \cdot 30 \cdot 0.6078d \text{ ohms.} \qquad (15)$$

The maximum value of b_{12} was for $x = 11$ cm. and was found to be 1,966 ohms or $65.5/v_0$ e.s.u. The maximum value of R' numerically was 344 ohms or $11.5/v_0$ e.s.u. Had the maximum value of R'^2 been sub-

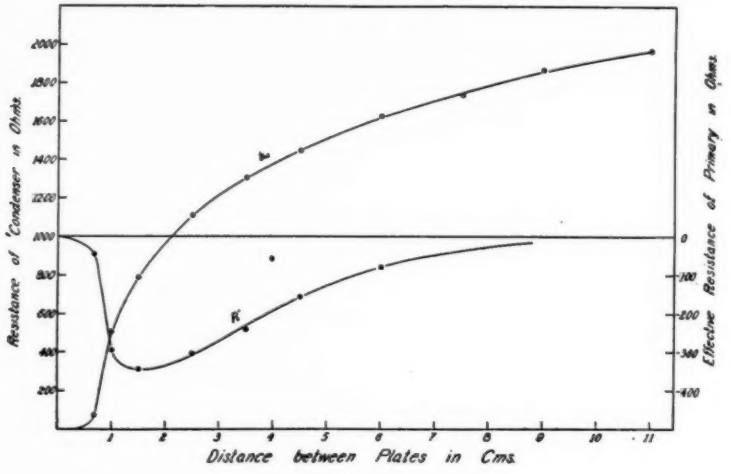

Fig. 10.

stituted for b_{22}^2 in the expression $(c_{22} - n^2 a_{22})^2 + p^2 b_{22}^2$ it would still be true that the resistance term would be negligible compared to the reactance term, though this would not be the case if the maximum value of b_{12} were so substituted. This is mentioned in an attempt to aid in the justification for the physical interpretation of the curves of Fig. 10, since it should be remembered that equation (1) holds only provided the resistance is negligible compared to the reactance. It may well be that a part of this measured condenser resistance or mutual resistance b_{12} is due to the fact that when the coupling becomes very loose the system ceases to be a non-radiant system and hence equation (1) would not hold.

It has been proved above beyond question that for small values of the distance separating two elastically reacting circuits theory and experiment agree and that as the distance between the circuit increases the condenser resistance increases, as is natural to expect. It would be interesting to investigate this condenser resistance further with a view to seeing how much of it could be explained as a true dielectric hysteresis and how much is due to radiation losses or other causes. Attention is here called to the shape of the curve of Fig. 10, which while not wholly

analogous to the curve of magnetization of ferromagnetic substances nevertheless is partly so.

In another paper important results in electromagnetic theory based upon the definitions of self and mutual elastance and self and mutual capacitance will be given and the application will be made to the thermionic tube.

Cordial acknowledgement for financial assistance is made to the Ohio State University for help in taking the observations and to the Committee on Grants of the Amer. Assn. for the Adv. of Sci. for help in curve drawing and making the calculations.

PHYSICAL LABORATORY,
OHIO STATE UNIVERSITY.

THE ACTION OF ROENTGEN AND GAMMA RADIATIONS UPON THE ELECTRICAL CONDUCTIVITY OF SELENIUM CRYSTALS.

BY A. M. McMAHON.

SYNOPSIS OF RESULTS.

Action of Gamma and Roentgen Radiations Demonstrated.—The increase in conductivity of selenium "cells" accompanying the absorption of X-rays has been found characteristic of individual crystals of metallic selenium. A similar effect upon the crystals has been observed to be produced by the absorption of the gamma rays of radium. The fact that a crystal fatigued to gamma rays is fatigued also to X-rays is evidence that the action in the two cases is similar. The indications are that the crystals are approximately twice as sensitive to gamma rays as to X-rays of the type used (L rays of tungsten).

New Electro-mechanical Properties.—Increase of mechanical pressure upon a crystal results in an increase of its sensibility both to X-rays and gamma rays. This is exactly the same result, qualitatively, as that secured by Brown in his study of the light effect (PHYS. REV., 4, p. 85).

Action of Separate X-ray Frequencies.—Unsatisfactory results obtained in the study of the strong lines of the L radiation of tungsten are thought to be due to the low intensities afforded by the X-ray spectrometer. Another method of attack is being planned.

Comparison of the Light, X-ray, and Gamma Ray Effects upon an Isolated Crystal.—Calculations made upon the basis of the energy absorbed indicate that a selenium crystal is most sensitive to gamma rays. The ratios of the change in conductivity to absorbed energy for exposures of one minute are 33.2, 58.5, and 108.9 $\left(\frac{\text{Mhos}}{\text{Joules}}\right)$, respectively.

I. INTRODUCTION

IN view of the established relationships between light, Roentgen and gamma rays, knowledge of their effects upon the electrical properties of crystals of metallic selenium assumes new interest. It has been shown[1] that the change in conductivity exhibited by these crystals on exposure to light depends upon the time, intensity, and character of the illumination. It is also known[2] that the sensibility (absolute ΔC) varies directly with the mechanical pressure to which the crystal is subjected. Other important facts concerning the action of visible radiations are available, but it is with those mentioned that this paper is mainly concerned. The effect of Roentgen rays upon films of metallic selenium has been investigated,[3] with the discovery that the form of the ΔC-time

[1] Brown, PHYS. REV., 33, p. 1.

[2] Brown, PHYS. REV., N.S., 4, p. 85.

[3] McDowell, PHYS. REV., 30, p. 474.

curves for this type of radiation is the same as that of those found for visible radiation, although the rate of recovery is much slower in the former case. The action of radioactive materials upon selenium "cells" has been known for some time,[1] although the separate action of the gamma rays had, within the knowledge of the writer, received no attention up to the time of the investigations reported upon in the present paper. It is thought that the continuation of this work should assist in relating properly the phenomena of conduction in solids with those of absorption, radiation, and atomic structure.

The experimental studies upon the action of X-rays, described in this paper, were initiated to secure information regarding the relation between the sensibility of these crystals and the frequencies of the strong lines in the characteristic L radiation of tungsten. Their change in conductivity on illumination has received a variety of theoretical treatments, among which that based upon a resonance hypothesis[2] offers considerable promise. According to this theory the electrons of the selenium atom whose radiation frequency corresponds, or nearly corresponds, to the frequency of the exciting agent, are loosened from their atomic bonds temporarily, and, in addition to the normal number free at any instant within the crystal, as indicated by the conductivity in the dark, contribute to the total current resulting from the application of a potential. A region of maximum sensibility has been found[3] in the red, and indications of a maximum in the ultra-violet. It was thought that if a region of maximum sensibility could be found within the range of X-ray frequencies the resonance theory would be much strengthened, and important evidence concerning the structure of the selenium atom obtained. Other experiments, incidental to this purpose, which have brought out a significant relation between the X-ray, gamma ray, and light effects, as regards the dependence of sensibility (absolute ΔC), upon mechanical pressure, constitute an important part of this report.

The studies herein described were made upon a single crystal selected from a lot prepared by Dr. W. E. Tisdale in the spring of 1916. They were of the hexagonal[2] variety secured by distillation in vacuo at 185° C. Investigations were in air at barometric pressure. The dimensions of the crystal chosen were roughly $3.2 \times .2 \times .1$ mm. It was mounted between carefully polished platinum electrodes, the mechanical pressure necessary being supplied by weights. In every case the direction of the rays was parallel to the long axis of the crystal.

[1] Brown, PHYS. REV., 26, p. 273.

[2] Pfund, PHYS. REV., 28, p. 324.

[3] Sieg and Brown, PHYS. REV., N.S., 4, p. 507.

II. THE ACTION OF X-RAYS.

Preliminary measurements upon the change of conductivity produced by single lines in the L radiation of tungsten indicated that the effect, if discernible with the apparatus used, is very small. A simple experiment was then planned and carried out to ascertain whether the addition of mechanical pressure would, as is the case when the exciting agent is visible light, produce an increase of sensibility.

The crystal was mounted in a metal box which was grounded. The leads were carried through lead tubing to a Wheatstone bridge of high resistance arms, situated in an adjoining room. All of this was found necessary to eliminate the electrostatic effects which otherwise resulted from the presence of the high potential transformer actuating the Coolidge tube furnishing the X-rays. In this experiment the total radiation from the tube, operating at 48.0 kv. and 3.5 amps. heating current, was used. It was found difficult to maintain the constancy of the input with better than 10–15 per cent. accuracy. Hence the distribution of points in Fig. 1. A heavy pendulum operating contact keys controlling

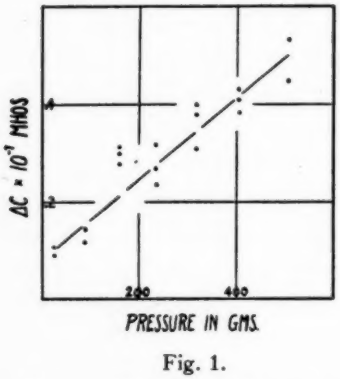

Fig. 1.

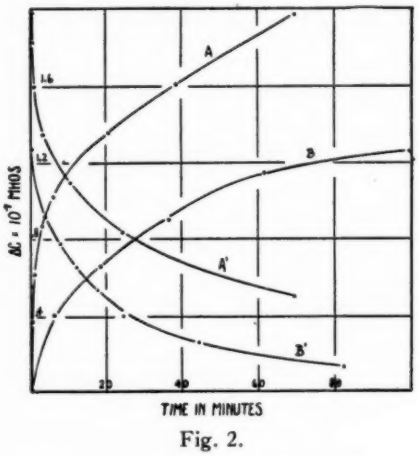

Fig. 2.

FIG. 1. The effect of change in mechanical pressure upon sensibility to X-rays.

FIG. 2. Excitation and recovery curves—X-rays. *A*, Excitation. Pressure 320 gms. Initial Conductivity 4.8×10^{-7} Mhos. *A'*, Recovery. *B*, Excitation. Pressure 320 gms. Initial Conductivity 4.6×10^{-7} Mhos. *B'*, Recovery.

the primary circuit of the transformer provided the means of keeping the time of exposure constant (one second), for different pressures. Time for recovery was allowed between observations. Brown and Clarke's method[1] was used in observing the change in conductivity. The results, plotted in Fig. 1, indicate an unmistakable increase of sensibility with pressure, similar to that found by Brown to exist when the exciting

[1] Brown and Clarke, PHYS. REV., 33, p. 53.

agent is light. Two other crystals studied in the same manner gave data which bear out this conclusion.

Following a procedure made obvious by these results, measurements were made anew upon five of the principal lines in the L radiation of tungsten (λ's-1.47, 1.27, 1.24, 1.09, 1.06 Å). Five hundred grams pressure was applied to the crystal—as much as was deemed advisable in view of the danger of fracturing. I am indebted to Dr. Elmer Dershem for the use of one of his X-ray spectrometers in these experiments as well as for initiation into the technique of its manipulation. Up to the present time, however, attempts to secure the effects of separate lines in this manner have been unsuccessful. Experiments are being considered which may solve the intensity difficulty, for this is thought to be the main reason for the failure.

It is very readily demonstrated that the total radiation from a Coolidge tube, operating upon a moderate energy input, produces a change in conductivity. Fig. 2 gives the results of two series of observations made upon the excitation and recovery characteristics of the crystal. Two additional experiments prove that these data come from changes in the conductivity of the crystal due to the absorption of X-rays. The apparatus was the same as described for the pressure-ΔC experiment. First, with no heating current flowing in the Coolidge tube filament, but with the customary 48.0 kv. potential applied, no galvanometer deflection was observed—*i.e.*, the balance of the bridge was maintained. Second, the introduction of a sheet of lead into the path of the rays from the target to the crystal resulted in a smaller total change than that produced in the absence of the lead. In making the measurements from which the data represented in Fig. 2 were computed a null method was used. The excitation and recovery of the crystal are so very much slower than the action of the galvanometer used that it was practical to change the balancing arm of the bridge by a convenient amount, usually 100 ohms, and observe with a watch the time required for the balance to be reattained.

III. The Action of Gamma Rays.

It was found time conserving to carry on experiments with gamma rays along with the X-ray studies, and in consequence of this practice a very interesting relation was discovered to exist between the gamma ray and X-ray effects, which, however, might have been predicted. In the first experiments with the crystal whose properties are here discussed gamma rays were used. When these were finished X-ray excitation and recovery curves were secured, six hours having been allowed for recovery. The results of the latter are given by curves B and B' of Fig. 2. By

comparison with the characteristics of other crystals from the same lot it was thought that the equilibrium value of the conductivity change, indicated by B, was too low. More time (48 hrs.) was allowed for recovery and curves A and A' secured, which show an equilibrium value comparing favorably with those secured for other crystals. Unquestionably, therefore, a crystal fatigued to gamma rays is also fatigued to X-rays, a result which is in accord with the view that these radiations are of a similar nature.

The effect of the gamma rays was obtained by lowering a thin glass vial containing a milligram of radium into proximity with the crystal through a hollow lead cylinder with walls a millimeter thick to absorb the alpha and beta rays. In these experiments the drift of the galvanometer spot was noted at ten second intervals and later translated into change in conductivity by proper calibration of the bridge. This alteration in method was found necessary in order to differentiate clearly between the effect of the gamma rays and the initial variation common in the balance of the bridge. Much more data than can be given here were taken to make sure of this point. It is thought that the action of

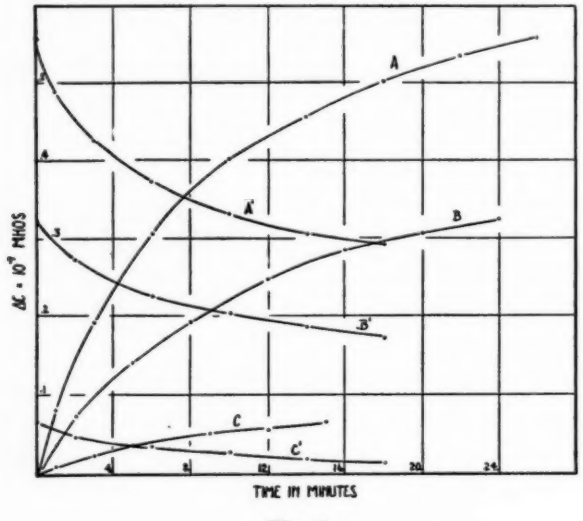

Fig. 3.

Excitation and recovery curves—gamma rays. A, Excitation. Pressure 320 gms. Initial Conductivity 5.53×10^{-7} Mhos. A', Recovery. B, Excitation. Pressure 216 gms. Initial Conductivity 5.08×10^{-7} Mhos. B', Recovery. C, Excitation. Pressure 24 gms. Initial Conductivity 1.25×10^{-7} Mhos. C', Recovery.

the gamma rays is established beyond question. Fig. 3 gives curves secured with the same crystal as before for three different pressures. The error due to variations in the balance of the bridge is probably less

than 1 per cent. for the maximum values of ΔC in curves A and B. The increase of sensibility with increase of mechanical pressure is unmistakable.

IV. A Comparison of the Light, X-ray, and Gamma Ray Effects.

It is of great importance to compare the X-ray, gamma ray, and light effects from the standpoint of absorbed energy. Although the data thus far available do not permit of direct comparison, it is possible by making certain assumptions to base a calculation upon them which leads to an interesting result. It is hoped that the additional measurements necessary for a more satisfactory comparison may be accomplished in the near future. The present calculations were made as follows.

The energy of the Roentgen rays was secured from the input to the Coolidge tube and the value for the efficiency of production at 48.0 kv. found by Rutherford.[1] The energy of the gamma rays was found from their known heating effects. An observation was made upon the change in conductivity undergone when light of .7 μ and known intensity was incident upon the crystal. Assuming the absorption law $I = I_0 e^{-\mu x}$ for Roentgen and gamma rays, and considering that all of the light entering the crystal must have been absorbed (the crystals are not transparent), we get the following results:

Radiation.	E_i = Incident Energy $\frac{\text{Ergs}}{\text{Sec.}}$.	E_a = Absorbed Energy $\frac{\text{Ergs}}{\text{Sec.}}$.	ΔC in 1 Min.
Gamma rays (Ra) . .	6.57×10^{-3}	3.74×10^{-4}	$.08 \times 10^{-7}$
X-rays (L of W). . . .	2.60×10^{-2}	1.06×10^{-2}	$.62 \times 10^{-7}$
Light (.7 μ)	1.84×10^{-3}	1.19×10^{-3}	$.15 \times 10^{-7}$

Benoist's relation between absorption and atomic weight was used in obtaining the X-ray absorption constant, $\mu = 1.64$. The assumption of Rutherfords' relation between density and absorption was necessary to secure the gamma ray absorption constant, $\mu = .184$. The distribution of X-ray, gamma ray, and light energy was considered uniform.

From these results and the intensity law,[2] $C = k I^{1/2}$, the change in conductivity when $E = 2.60 \times 10^{-2}$ was calculated for each type of radiation. The absorbed energy was found, also, and the ratio, $\Delta C/Ea$, formed, viz.:

Radiation.	ΔC in 1 Min.	E_a in $\frac{\text{Ergs}}{\text{Sec.}}$.	$\frac{\Delta C}{E_a}$.
Gamma rays.	$.16 \times 10^{-7}$	1.47×10^{-3}	108.9×10^{-7}
X-rays	$.62 \times 10^{-7}$	1.06×10^{-2}	58.5×10^{-7}
Light	$.56 \times 10^{-7}$	1.69×10^{-2}	33.2×10^{-7}

[1] Rutherford, Phil. Mag., 30, p. 361.

[2] Nicholson, PHYS. REV., N.S., 3, p. 1.

Although the figures resulting from these computations are in the nature of approximations it is hoped that their order of magnitude may prove suggestive of the possibilities in this line of work.

The conclusion of the greater sensibility to gamma rays seems quite certain, however. For if instead of the above square-root intensity law we assume the linear law[1] for faint illumination, the comparison is even more favorable to the gamma rays. Discussion of just what this apparent difference may mean is postponed until a more complete experimental study can be made.

In conclusion I wish to express my appreciation of the interest the staff of the Department of Physics of the University of Iowa has taken in these problems. Especially do I wish to thank Dr. F. C. Brown for his suggestions and encouragement throughout the progress of the work.

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STATE UNIVERSITY OF IOWA.

[1] Brown and Sieg, PHYS. REV., N.S., 2, p. 487.

THE EFFECT OF TEMPERATURE UPON THE INFRA-RED ABSORPTION OF CERTAIN GLASSES.

By G. E. Grantham.

Synopsis.

Change of the infra-red transmission of glass with rise of temperature.—Dr. K. S. Gibson has studied the effect of temperature rise upon the absorption spectra of certain glasses in the visible region. He found a shift toward the longer wave-lengths and a decrease in transmission. The infra-red transmission (0.6 μ to 4.0 μ) of the same specimens has been studied at 80° C., 307° C. and 440° C. Rise of temperature increases the transmission in the region of an absorption band. There is a shift of the transmission bands toward the longer wave-lengths. The same results are obtained whether one observes a series of ascending or a series of descending temperatures.

THE effect of temperature upon infra-red absorption spectra has been investigated by L. C. Martin[1] for black biotite. It was found that in general the absorption was greatly increased by a rise of temperature and that this effect was reversible. He also found that a rise of temperature had a tendency to obliterate an absorption band which existed at a lower temperature. With rise of temperature the maximum of transmission moved toward the less refrangible part of the spectrum. The suggested explanation of these effects is that a temporary chemical change within the crystal is caused by a rise of temperature.

K. S. Gibson[2] has investigated the effect of temperature upon the absorption spectra of several glasses of known composition in the visible region (0.5 μ–0.7 μ). He found that there was an increase of absorption with rise of temperature and that this was accompanied by a shift of the less refrangible edge of an absorption band toward the red end of the spectrum. On account of these changes the edge of the band became less steep and there was therefore a change in color of the specimen. The object of this investigation was to study the effect of temperature upon the infra-red absorption spectra of the same specimens used by Gibson, and to see whether the shift of the edge of an absorption band, as found by him, was coincident with a shift of a transmission band lying largely in the infra-red or resulted in a narrowing of such a transmission band.

[1] Proc. of the Royal Soc., Series A, Vol. 96, 1919.

[2] The Physical Review, N.S., Vol. VII., 1916.

The glasses used were:

No.	Color.	Coloring Material.	Glass.	Thickness.
1	Red.....	Cadmium-selenium	Zinc	1 mm.
2	Orange.....	Cadmium-selenium	Non lead	2 mm.
3	Light amber.....	Cadmium-selenium	Borosillicate	2 mm.
4	Lemon yellow.....	Cadmium-sulphide	Zinc	2 mm.

These glasses have transmission curves which are very similar and investigation of these specimens indicated the advisability of trying a specimen with well defined transmission and absorption bands. A specimen of Corning G.585 blue glass of 1.98 mm. thickness was chosen.

These specimens were placed in a furnace and the absorption spectra studied between 0.6 μ and 4.0 μ for these temperatures; 80° C., 307° C. and 440° C.

APPARATUS.

The Furnace.—The construction of the furnace is shown in Fig. 1. A cylindrical piece of iron, *I*, 12 cm. long and 8 cm. in diameter was

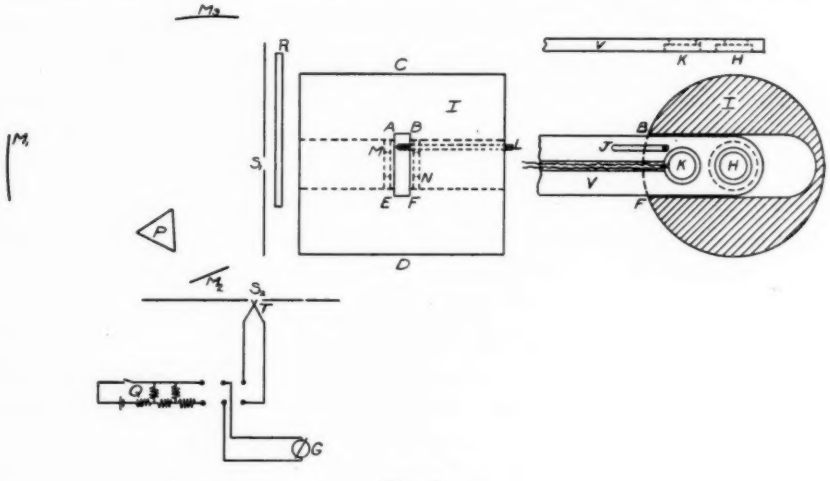

Fig. 1.

chosen as the core of the furnace. A hole 2.5 cm. in diameter was bored lengthwise through its center. The cylinder was then cut in halves at *CD* and a rectangular slot *ABEF* was milled into the end of each half and the halves fitted together and fastened by screws. An iron slide *V* was made which would fit the slot in *I* snugly. Two holes *K* and *H* 2.2 cm. diameter were bored half way through the slide, and, then using the same center, a hole 1.7 cm. diameter was bored the remaining distance through the slide. This afforded a shoulder against which the specimen

could be fastened by means of cement. A slot J cut through the slide served by means of the stop L to keep the holes H and K concentric with the cylindrical hole in the block I. Two iron washers M and N of internal diameter 1.5 cm. served the double purpose of diminishing the effect of reflection in the furnace and to correct for any error due to the hole H not being in the same position relative to the furnace as K, when the slide was at the limits of its path as determined by the slot J. The cylinder was heated by means of an electric current passing through a coil of iron wire, which was wound around the cylinder between layers of asbestos paper soaked in water-glass. At first the ends of the cylinder were covered with thin sheets of mica. This gave a large percentage of reflection and trial showed that if the bulb of the lamp giving the source of radiation was placed against the end of the furnace, there was no difficulty in keeping the sample at a constant temperature. The specimen was placed in the hole K and the junction of a copper-constantin thermocouple, was placed in contact with the specimen. The leads were buried in fire clay in the groove cut in the slide. The thermocouple was placed in conjunction with a Wolff potentiometer and was calibrated at 99.2° C., 232° C., 419° C. and 630° C. corresponding to the boiling point of water, and the melting points of tin, zinc and antimony respectively. The maximum temperature variation from the values given was probably not greater than five to eight degrees.

The Spectrometer.—A Hilger infra-red constant deviation spectrometer equipped with a Coblentz bismuth-silver thermopile was used. Rays on entering the collimating slit S_1, were rendered parallel by the concave nickel steel mirror M_1 of 27 cm. focal length, and 2.7 cm. aperture, and passed through the rock salt prism P to the Wadsworth[1] mirror system. The polished faces of the prism were 3.2 cm. high and 4.2 cm. long. After reflection by the plane mirror M_2 and the concave mirror M_3, identical with M_1 an image of the spectrum was formed on the slit S_2. The prism and plane mirror were mounted on a table which was rotated by a screw to which was attached a drum, calibrated to read wave-lengths between 0.5 μ and 10.0 μ. When the instrument was properly adjusted each ray which entered the slit S_1 passed through the prism at minimum deviation. The faces of the rock salt prism and the concave mirrors were repolished at the beginning of this investigation, and the most careful adjustment of the prism for minimum deviation for the D lines, gave the following values for three absorption bands of water and the carbon dioxide emission band respectively 1.48 μ, 1.98 μ, 3.0 μ and 4.36 μ. These bands as observed by Coblentz[2] occur at 1.5 μ, 2.0 μ, 3.0 μ and

[1] Phil. Mag., S. 5, Vol. 38, 1894.

[2] Bulletin of the Bureau of Standards, Vol. 7, No. 4.

4.4 μ respectively. These points were checked from time to time throughout this investigation, and it was found that the calibration did not change as long as no attempt was made to remove the prism from the spectrometer table. The spectrometer was covered completely by a glass case, which was in turn covered by a sheet iron case. The inside walls of the glass case were covered with black cloth to prevent reflection. A 2.5-watt electric lamp was kept burning continuously under the spectrometer so that the temperature of the instrument was above that of the surroundings. The drum was turned by means of a belt, which passed around the drum, and a pulley located under the table upon which the instrument was mounted. Within the glass case were kept several beakers containing P_2O_5 to prevent moisture from attacking the faces of the prism. During these investigations the two slits S_1 and S_2 were 0.25 mm. wide. The range of spectrum embraced by this slit width at the thermopile end is indicated for four regions in the spectrum at the bottom of each curve.

The Galvanometer.—A Coblentz[1] astatic galvanometer was used. The astatic system consisted of two groups of four magnets each. The magnets were about two millimeters long. This system was suspended by a very delicate quartz fiber so that each magnet group hung at the center of a pair of coils embedded in Swedish iron. The galvanometer was mounted on a concrete pier, the top of which was covered by 2.5 cm. of sheet transformer iron. Immediately surrounding the galvanometer was a cylinder of transformer iron, the wall of which was 1 cm. thick. Surrounding this were five cylinders of increasing diameter. These cylinders were cut from wrought iron gas pipe and the walls of each were approximately one centimeter thick. Covering the galvanometer and cylinders was a two centimeter layer of sheet iron. The sensibility of the galvanometer was adjusted by means of control magnets placed under the galvanometer and cylinders. Throughout this investigation the sensibility did not vary much from 3.3×10^{-11} amperes per mm. at three meters distance. This sensibility was measured by means of the testing box Q, which was furnished with the galvanometer. The leads between the galvanometer and thermopile were in iron conduit which was grounded. Even with these precautions, changes in current throughout the building caused induction effects, which were troublesome in the day time, and most of the data reported on here were obtained at night. No scale deflection greater than 35 cm. at three meters

[1] Bulletin of the Bureau of Standards, 4, 1908.
Bulletin of the Bureau of Standards, 9, 1912.
Scientific Papers of the Bureau of Standards, No. 282.

distance was used. The resistance of the galvanometer and thermopile were 8.9 ohms and 9.6 ohms respectively.

The Source of Radiation.—The source of radiation was a 400-watt nitrogen-filled tungsten lamp, which was connected across the terminals of a 120-volt storage battery.

Method of Taking Observations.

The trials at the lower temperature were made with the specimen in the furnace, when no current was flowing in the heating coils. An equilibrium temperature of about 80° C. was attained due to radiation from the source. For these trials the order of observations were as follows: The drum of the spectrometer was set for a given wave-length.

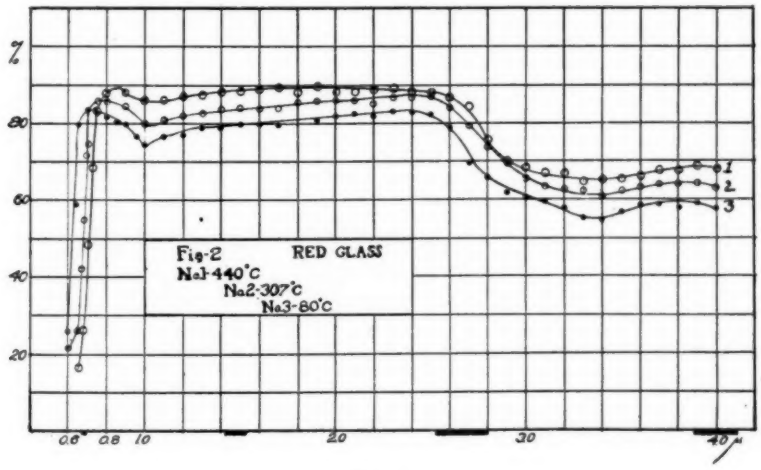

Fig. 2.

With the shutter R covering the slit S_1, the zero of the galvanometer was determined. Then with the radiation from the source passing through the specimen the shutter was opened and galvanometer deflection d_1 recorded. The slide V was now quickly pulled out, allowing the radiation to fall directly on the slit and the galvanometer deflection d_2 taken. The shutter R was again closed and the zero determined. This process was repeated until consistent results were obtained. For portions of the spectrum, where the energy emitted by the source was small, the mean of twenty such trials was used to locate the point on the curve. The average number of trials for each point was six. The ratio of d_1 to d_2 when multiplied by 100 is called the percentage transmission for that wave-length. This value was corrected for reflection and the value of transmittance obtained in the following manner: assuming the index of

refraction to be 1.5 and the Fresnel formula for the per cent. of reflection at normal incidence $[(n-1)/(n+1)]^2$ the per cent. reflected at each surface of the glass became 4 per cent. Assuming this reflection to remain constant throughout the range 0.6 μ to 4.0 μ the transmittance was obtained from the expression:

$$\text{Transmittance} = T = \frac{d_1}{.96^2 d_2} \times 100.$$

Although the percentage of reflection decreased with increase of wave-length this assumption introduced a maximum error of less than 2 per cent. Rubens[1] has measured the dispersion of flint glass and found the value $\mu = 1.7510$ for $\lambda = 0.5893\ \mu$ and $\mu = 1.6688$ for $\lambda = 4.12\ \mu$. If these specimens, with an index of refraction approximately equal to 1.5,

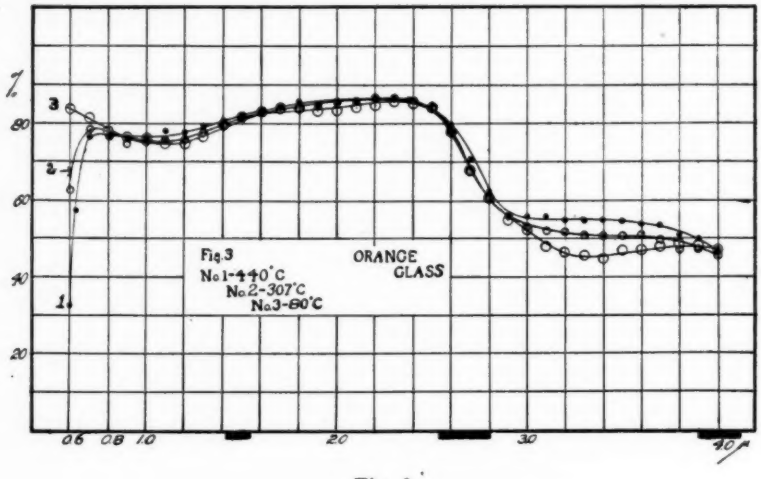

Fig. 3.

should change proportionately to the flint glass, the value for the index of refraction at $\lambda = 4.12\ \mu$ would be $\mu = 1.43$, which would cause 3.13 per cent. reflection at each surface. This method also neglects any change in the index of refraction of the glass with rise of temperature.

For trials in which the furnace was heated it was found that beyond 2.0 μ the radiation from the furnace and the specimen was an appreciable factor. For example, as seen from Table I. for the red glass at 4.0 μ d_1, the galvanometer deflection caused by the radiation, when the tungsten lamp was sending radiation through the glass, was 145 mm. and the corresponding deflection d_2 when the glass was removed was 167 mm. For the same wave-length the deflection d_3, taken when the tungsten lamp was turned off, was 90 mm. with the glass in the center of the fur-

[1] Wied. Ann., 53, p. 276, 1894.

nace and the deflection d_4 taken when the glass was removed and the lamp off was 80 mm. Thus between 2.0 μ and 4.0 μ the order of taking observations was as follows: The drum was set at a certain wave-length, the shutter closed and the zero of the galvanometer determined. With the lamp turned off a deflections d_3 was taken with the glass in the center of the furnace. The slide V was then quickly moved to the other side and galvanometer deflection d_4 read. The zero was again determined and the deflection d_1 and d_2 taken as previously described. The transmittance was then calculated from the expression

$$T = \frac{d_1 - d_3}{0.96^2\,(d_2 - d_4)} \times 100.$$

Discussion of Results.

A table of observed and computed data is shown in Table I. The effects are shown diagrammatically by the figures Nos. 2, 3, 4, 5 and 6.

Glass No. I.
Temperature 440° C.

μ.	d_1, mm.	d_2, mm.	d_3, mm.	d_4, mm.	$\frac{d_1 - d_3}{d_2 - d_4} \times 100$.	Av. %.	Trans.
.65	3	20	0	0	15	15	16.2
	3	20			15		
	3	20			15		
.75	50	65	0	0	77.0	76.7	83.0
	50	65			77.0		
	47	62			76.0		
1.0	81	102	0	0	79.4	79.3	85.9
	81	102			79.4		
	80	101			79.2		
1.5	121	148	0	0	81.8	81.3	88.0
	120	149			80.6		
	120	147			81.6		
2.0	150	185	2	2	81.0	81.0	87.7
	150	185	2	2	81.0		
	150	185			81.0		
2.5	157	189	13	11	81.0	80.8	87.5
	157	190	13	11	80.4		
	155	186			81.2		
	159	192			80.6		
3.0	139	192	41	38	63.6	63.1	68.4
	139	195	41	38	62.5		
	139	192			63.6		
	139	194			62.8		
3.5	169	213	85	73	60.0	60.3	65.3
	169	212	85	73	60.4		
	169	212			60.4		
4.0	145	167	90	80	63.2	63.2	68.4
	145	167	90	80	63.2		
	145	167			63.2		

Fig. 2 indicates for the red glass the same shift in the visible region as was found by Gibson. This sample shows a decrease in absorption with rise of temperature throughout the whole range except for wave-lengths

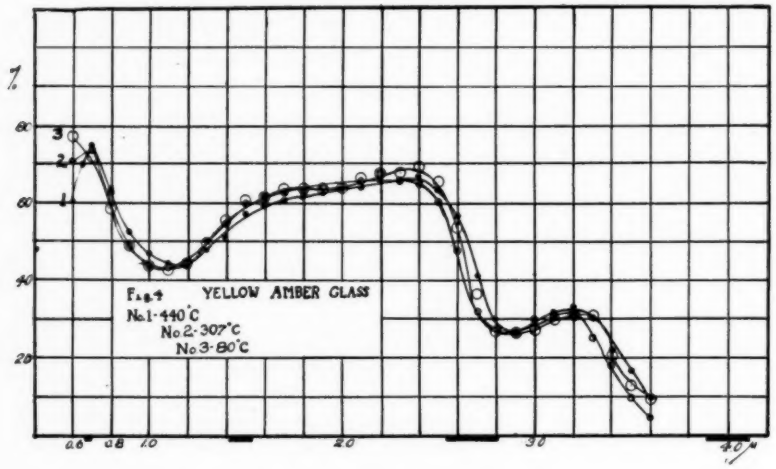

Fig. 4.

less than 0.75 μ when the absorption increases with a rise of temperature. There is evidence of a shift of the whole transmission band, extending from about 0.7 μ to about 2.7 μ, toward the less refrangible portion of the

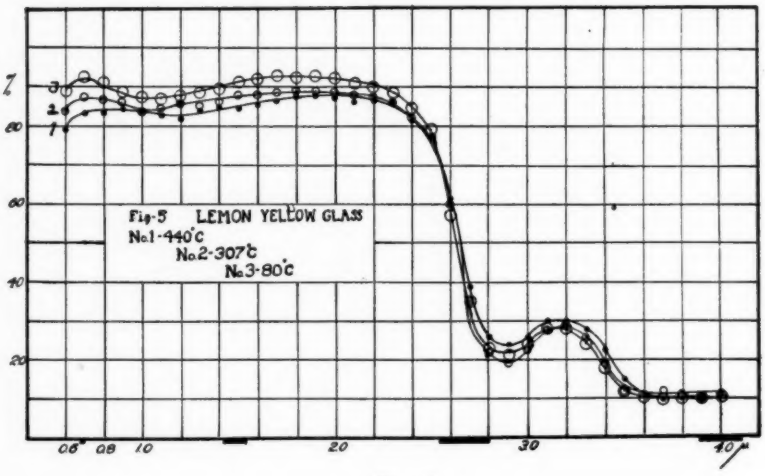

Fig. 5.

spectrum. The absorption band at 1.0 μ is less marked at higher temperatures. The absorption band at 3.35 μ although less prominent than the band at 1.0 μ is modified so as to make the percentage of trans-

mittance more uniform in this region. This specimen exhibited no sharp absorption bands in this region.

The percentage transmittance for the orange glass is shown in Fig. 3. There is indication of a slight shift with a rise of temperature of the transmission band extending over about the same region as the transmission band for the red glass. There is also a very slight increase in transmittance throughout this transmission band. At the 3.3 μ absorption band there is a marked increase in the transmittance with rise of temperature. Fig. 4 shows a shift of the whole transmission band toward the longer wave-lengths with a rise of temperature and a slight decrease of transmittance except in the region of absorption bands, when the transmittance increases. The absorption band at 1.1 μ shows evidence of a shift toward the longer wave-lengths.

Fig. 5 shows unmistakably, at higher temperatures, a decrease of transmittance throughout the range from about 0.6 μ to 2.4 μ with the highest temperature in the region of the absorption band at about 2.9 μ the transmittance is higher than at lower temperatures.

With a specimen having sharp absorption bands, as shown in Fig. 6,

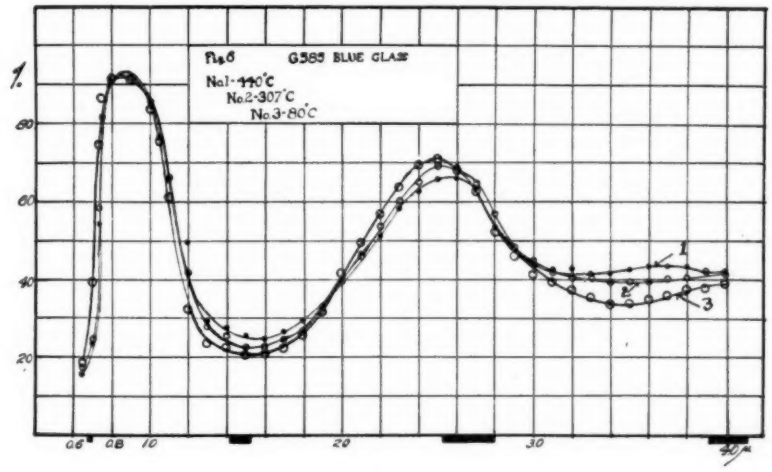

Fig. 6.

there is further evidence that an increase in temperature produces a decrease in absorption in the region of absorption bands in the infra-red. The peaks of the transmission bands are shifted toward the longer wave-lengths at higher temperatures. This is brought about by an increase in absorption on the long wave-length side of an absorption band and a decrease of absorption on the short wave-length side of an absorption band. The net result of this is to broaden the absorption band without

any apparent shift in the peak of an absorption band. This applies particularly well to the absorption band having a maximum between 1.3 μ and 1.8 μ.

In general the following conclusions may be drawn regarding the effect of a rise of temperature upon the absorption spectra of these glasses.

1. Rise of temperature decreases slightly the absorption in the region of an absorption band.

2. There is a shift of the transmission bands toward the longer wavelengths, which is greater on the more refrangible edge than on the less refrangible.

3. The same results are obtained whether one observes a series of ascending or a series of descending temperatures.

This investigation was suggested by Professor R. C. Gibbs; I am indebted to him for many helpful suggestions throughout the work. I am also indebted to my wife, Margaret Grantham, for assistance in taking the data and computing results.

CORNELL UNIVERSITY,
ITHICA, N. Y.

ERRATA

Vol. XV, June, 1920 on page V of the contents of Vol. XV, the contents for April should read as follows:

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Vol. XVI, July, 1920, article by Willard J. Fisher entitled "Note on the End Correction in the Determination of Gas Viscosity by the Capillary Tube Method, the word "*not*" should be insert in the fourth line from the bottom of page 83 so as to read: "is surely *not* an illustration of stream line flow."

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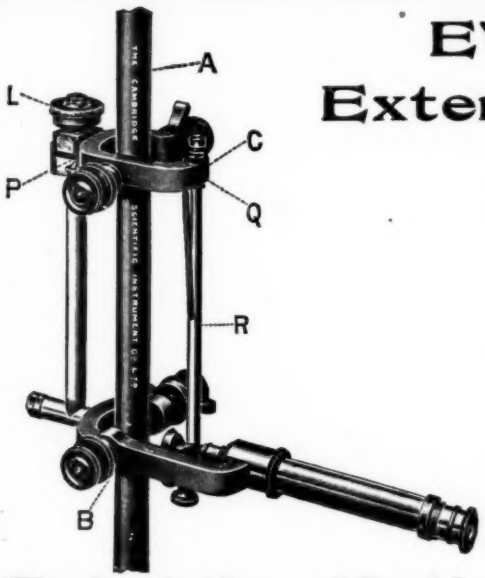

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Revised, May, 1920

Every article in THE PHYSICAL REVIEW is to be preceded by a synopsis prepared by the author and submitted by him with the manuscript. The synopsis is intended to serve as an aid to the reader by furnishing an index and brief summary or preliminary survey of the contents of the article; it should also be suitable for reprinting in an abstract journal so as to make a reabstracting of the article unnecessary. *The synopsis should, therefore, summarize the information completely and precisely.* Furthermore, in order to enable a reader to tell at a glance what the article is about and to enable an efficient index of its subject matter to be readily prepared, *the synopsis should contain a set of subtitles which together form a complete and precise index of the information contained in the article.* This requires at least one and often several subtitles even for a short synopsis.

In the preparation of synopses, authors should be guided by the following rules, which are illustrated by the synopses in the PHYSICAL REVIEW for January, February and March, 1920.* The new information contained in an article should first be determined by a careful analysis; then the subtitles should be formulated; and finally the text should be written and checked.

Rules

1. *Material not new* need not be analyzed or described; a valuable summary of previous work, however, should be noted.

2. *The subtitles should together include all the new information;* that is, every measurement, observation, method, improvement of apparatus, suggestion and theory which is presented by the author as new and of value in itself.

3. *Each subtitle should describe the corresponding information so precisely* that the chance of any investigator being misled into thinking the article contains the particular information he desires when it does not, or *vice-versa,* may be small. "X-ray patterns of metals" is too broad unless all metals have been studied, for an investigator may be interested, at the time, in only one metal; but "X-ray patterns of aluminum, effect of rolling" evidently satisfies this rule. It is particularly desirable that ranges of variation of temperature, wave-length, pressure, etc., be given in the subtitle.

General subtitles, such as "Object" or "Results," should not be employed, as they do not help to describe the specific information given in the article.

4. *The text should summarize the author's conclusions and should transcribe numerical results of general interest,* including those that might be looked for in a table of physical and chemical constants, with an indication of the accuracy of each. It should give all the information that anyone, not a specialist in the particular field involved, might care to have in his note book.

5. *The text should be divided into as many paragraphs* as there are distinct subjects concerning which information is given. Parts of subtitles may be scattered through the text but the subject of each paragraph, however short, must be indicated at the beginning.

6. *Complete sentences* should be used except in the case of subtitles. The synopsis should be made as readable as the necessary brevity will permit.

*The rules and illustrative synopses were prepared by G. S. Fulcher of the National Research Council.

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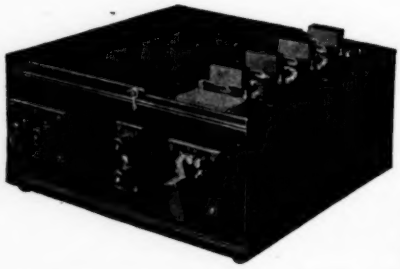

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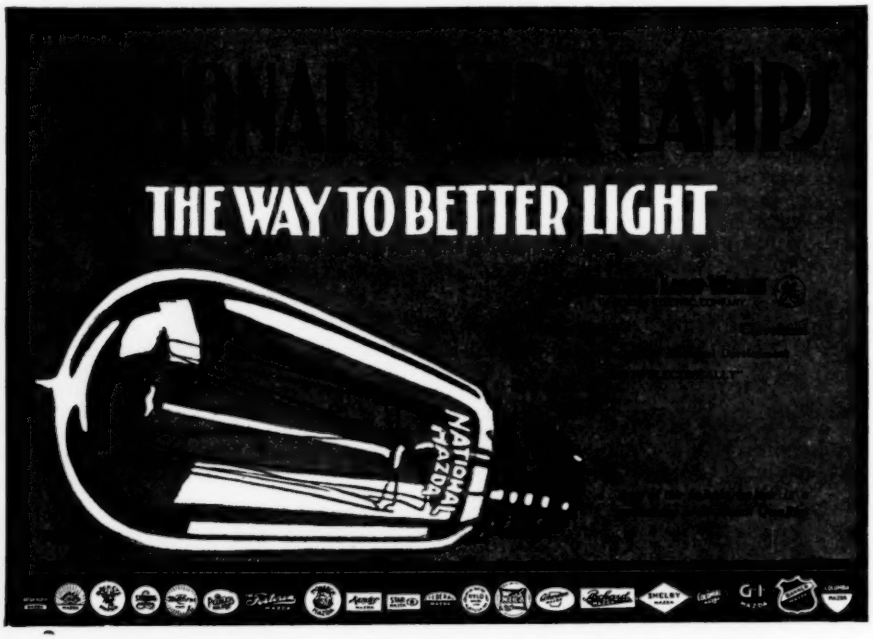

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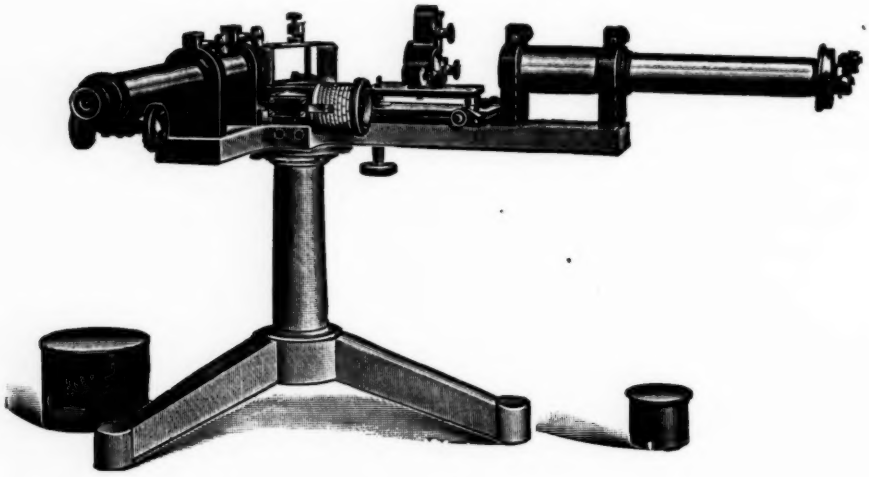

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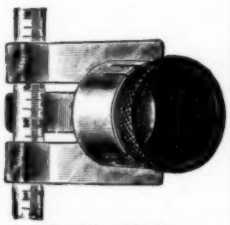

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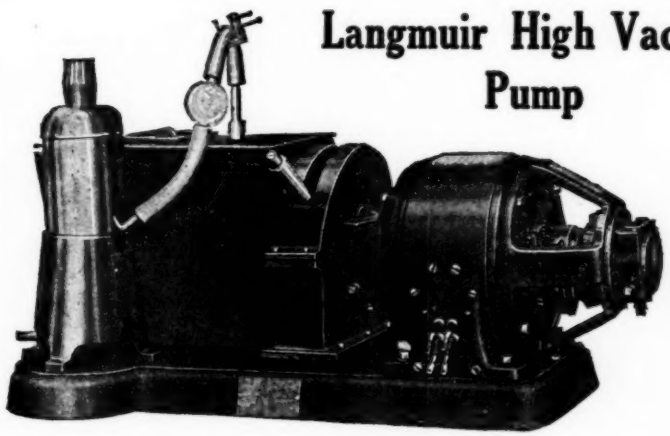

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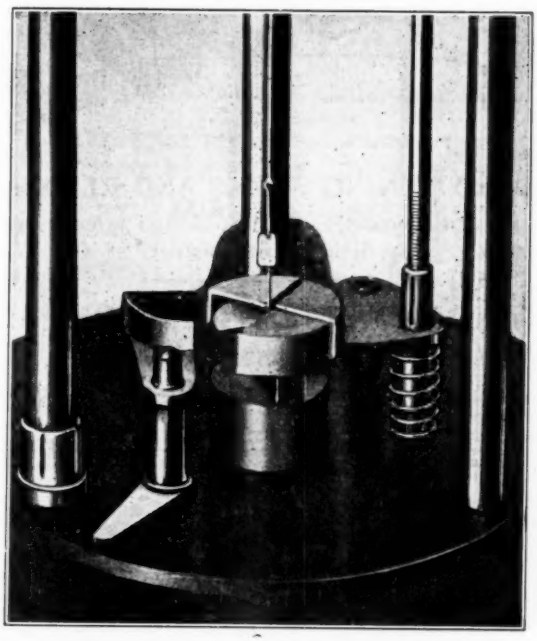

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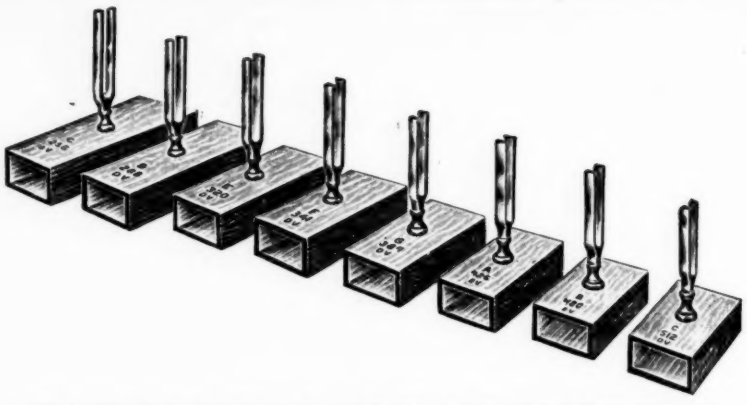

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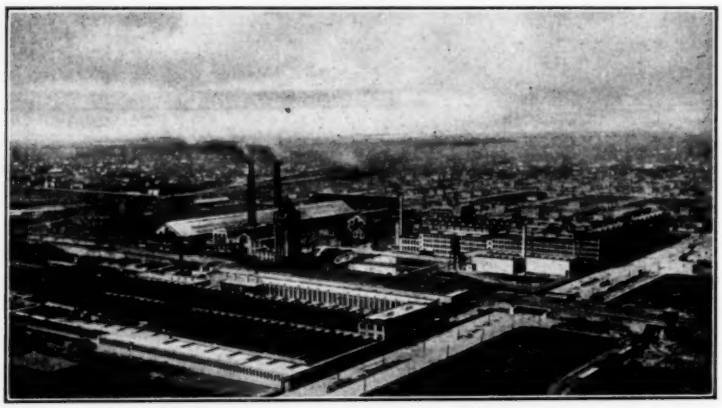

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